Fish community interactions with Very Low Head (VLH) turbine technology

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B.Sc. (Hons) Trent University, 2016

A thesis submitted to

the Faculty of Graduate and Post-Doctoral Affairs

in partial fulfillment of the requirements for the degree of

Masters of Science

in

Biology

Department of Biology

Carleton University

Ottawa, Ontario

September, 2019

Abstract

There is a general shift in hydropower towards more cost effective and environmentally friendly hydroelectric generation. As a result, new turbine technologies like the very low head (VLH) turbine have been developed. The first VLH turbines in Canada were put into operation at Wasdell Falls on the Severn River, ON, with the possibility of future deployments across Canada. However, there is lack of information regarding the risk that these purportedly “fish friendly” turbines pose to North American fish species. Therefore, to rectify this, I carried out a two-part study, the results of which when combined, would inform overall risk of the turbine to fish. In the first part of this study (Chapter 2) I assessed risk of entrainment through the VLH turbines using acoustic telemetry based on fish use of the forebay areas upstream from the infrastructure. Here I found that that entrainment (fish passage) through the VLH turbines of tracked fish did not occur over the course of one year. I also found that half of the tagged species made use of the forebay areas and that forebay usage occurred at similar species proportions to the original tagged sample indicating that usage was not species specific. I also found that usage of the VLH forebay was limited. In the second part of this study (Chapter 3), risk was assessed based on the specific injury and mortality rates resulting from entrainment. To determine turbine specific injury and mortality rates, I experimentally introduced fish into the turbines and subsequently recaptured fish downstream using balloon tags. Research focused on largemouth bass (*Micropterus salmoides*), smallmouth bass (*Micropterus dolomieu*), rockbass (*Ambloplites rupestris*), walleye (*Sander vitreus*) and Northern pike (*Esox lucius*) spanning body sizes of 17 to 69cm. Using pre-entrainment and post-entrainment assessments we were able to determine injury and mortality incidences. Analysis of the data showed minimal differences between control (no entrainment) and treatment (entrainment) groups. Only one fish (representing 1.16% of total entrained fish of all species and 6.25% of entrained pike) was killed by turbine strike otherwise abrasion related injuries were the most common. These results suggest that entrainment events by the VLH turbines are rare on the species that were studied, and that entrainment by VLH turbine has minimal effects on the fish with very low mortality. Overall, the findings suggest that the risk posed by the VLH turbines is low for the species and life stages studied here.

Acknowledgements

I would like to thank my co-supervisors Dr. Steven Cooke and Dr. Karen Smokorowski for their support, patience and advice throughout my Masters. I would also like to thank Evan Timusk for his advice and input, especially in building the equipment for this project. Thank you to my committee members Dr. Gabriel Blouin-Demers and Dr. Michael Donaldson for their advice and feedback. I would like to thank all those who helped with field work: Dirk Algera, Stephanie Best, Anne-Sophie Fabris, Amanda Jeanson, Marla Thibodeau, Sarah Walton, and Jenna Webb. I would like to thank Jacqueline Chapman, Dr. Graham Raby, Benjamin Hlina and Dr. Elodie Lédée for their help with R in both statistics and working with the telemetry data. I thank Glenn-Hepinstall for helping us conduct work at the study site, and Enbridge for allowing us access to the study site. I must also acknowledge the support and encouragement of my parents and my girlfriend over the last few years, which has helped me immensely. Funding for this project was provided by Fisheries and Oceans Canada and the Natural Sciences and Engineering Research Council of Canada.

Co-Authorship Statement

Chapter 2: Interactions of a temperate North American fish community with a very low head hydropower facility in Ontario, Canada

Erik I. Tuononen, Elodie J.I. Lédée, Karen E. Smokorowski, Evan R. Timusk, Steven J. Cooke

This manuscript is planned for submission to a peer reviewed journal. The project was conceived by Cooke and Smokorowski. Field work was carried out by Smokorowski, Timusk, and Tuononen. Data analysis and interpretation was conducted by Lédée and Tuononen. Manuscript was written by Tuononen, and all co-authors contributed to feedback.

Chapter 3: Effects of Entrainment Through Very Low Head Turbines on a Representative North American Freshwater Fish Community

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This manuscript is planned for submission to a peer reviewed journal. The project was conceived by Cooke and Smokorowski. Field work was carried out by Smokorowski, Timusk, and Tuononen. Data analysis and interpretation was conducted by Tuononen. Manuscript was written by Tuononen, and all co-authors contributed to feedback.

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Hydropower

As the global requirement for energy increases so to does the need to meet this demand but to also balance this with ecological concerns relating to climate change. Hydroelectric power generation is a cleaner alternative to generation with fossil fuels and can have a smaller ecological footprint. Hydropower is one of the oldest and most common forms of electrical generation globally. As of 2016 hydroelectric generation accounted for 71% of global energy production (Moran, Lopez, Moore, Müller, & Hyndman, 2018). Many countries with fluvial systems have the potential to make use of this type of power generation. Historically hydroelectric turbines have required high-head structures with the ability to store large amounts of water. Head height is the distance between water intake and outflow needed to operate a turbine. In high head operations the head height is >100 m tall, with low head sites having <30 m (Loots, Dijkb, Bartac, Vuurend, & Bhagwane, 2015). The construction of these projects can have significant negative environmental consequences and both terrestrial and aquatic ecosystems can be damaged or changed drastically. Large reservoirs required for water storage to operate these turbines can flood large areas causing ecological damage (Gleick, 1992). Furthermore, reservoirs created for this purpose disrupt thermal and flow regimes (Zhong & Power, 1996). In addition to the ecological impacts, social impacts can be severe, with poorer communities often suffering due to forced relocations to accommodate reservoir footprints (Moran et al., 2018).

Another concern for hydroelectric generation is that of the effects of turbine entrainment on fish (Čada, 2001). Turbine entrainment occurs when a fish passes through a hydroelectric turbine (either volitionally or non-volitionally). Entrainment of migratory fish has been well studied however entrainment of resident fish has not been as thoroughly examined (Martins et al., 2013). Turbine entrainment is a documented hazard to fishes with different turbine designs having effects and severities (Mueller, Pander, & Geist, 2017). Entrainment through a conventional (high-head) hydroelectric turbine can cause injury or mortality through a number of different mechanisms. Mechanical injury, impingement, shear forces, amputation, spinal deflections, internal injuries barotrauma, and abrasion related injuries have all been recorded as the result of turbine entrainment (Čada, 2001; Mueller et al., 2017). Many of these may cause sublethal injury, while other injuries may be fatal outright.

In recent years the hydroelectric industry and various stakeholders have been driving interest in lower impact, low head hydroelectric generation. Low head turbines have the benefit of providing hydroelectric generation with a lower ecological footprint and can be put into operation on underutilized sites with the potential to support hydrogeneration capabilities. The potential benefit of low head hydropower is possibly largest in the developing world. Low head hydroelectric generation allows for power generation which can be built using smaller economic investments and maintained with lower costs (Elbatran, Yaakob, Ahmed, & Shabara, 2015). This is in direct contrast to the centralized hydroelectric megaprojects which are currently often pursued in the developing world (Moran et al., 2018). Low head hydropower also has the ability to provide more remote communities with the ability to have their own hydroelectric generating capabilities (Elbatran et al., 2015). These countries which are still developing hydroelectric generating infrastructure could also reap the ecological benefits of newer low head hydroelectric generating facilities with a much smaller ecological footprint. Low head hydroelectric facilities are typically less costly to construct compared to conventional hydroelectric facilities. Money is saved mostly in the construction of the structure providing sufficient head (which maybe not even be needed if the turbine can be retrofitted on pre-existing infrastructure).

Low head hydropower in developed countries has the potential to provide many of the same benefits, especially in terms of lower constructions costs and the ability to make use of an underutilized resource. In Canada, there are approximately 200,000 people in 300 remote communities without access to clean electricity (Ranjitkar, Huang, & Tung, 2006). Low head hydropower has the potential to provide these communities with cleaner hydroelectric generation, by making use of local waterways. There are approximately 80,000 sites across North America with the potential to support low head hydroelectric generating operations (Kemp, Williams, Sasseville, & Anderson, 2014). As a result of this underutilized resource, many are looking towards harnessing energy from the smaller systems. There are a number of different low head hydroelectric turbines which have been trialed and in recent years there have been many innovations in low head hydroelectric turbine designs. These new technologies and types of turbines allow power to be generated in previously nonviable sites.

One such recent development is that of the Very Low Head (VLH) series of hydroelectric turbines. These turbines like many other low head turbines, have a large number of potential benefits over large scale conventional hydropower. The construction costs for the creation of the water retention device are lower as less material is needed, and these turbines can make use of pre-existing low head infrastructure. For example, existing water control infrastructure such as water control dams or weirs can be retrofitted to support a VLH turbine. The main source of cost in setting up a VLH facility would be in the purchasing and installation of the turbine. These turbines use a large Kaplan turbine with rotatable blades that have a large and rounded leading edge. These blades can be rotated to adapt to flow conditions and can even stop the turbine if fully closed. The VLH turbine is mounted near the surface at angle of 30° - 50° and can operate at head heights of 1.4 m - 4.2 m producing a generating capacity of up to 500 kW (Cooke, Hatry, Hasler, & Smokorowski, 2011; Fraser & Deschênes, 2007; Kemp et al., 2014). Since less water flow is required to operate these turbines, upstream water storage has a smaller footprint. This is an aspect which lends itself well to making use of low head resources in settings where expansion of the water storage capabilities is not possible (in urban environments for example).

Another purported benefit of this type of turbine is that of “fish friendliness” which has garnered interest in its own right (Fraser & Deschênes, 2007; Kemp et al., 2014). This claim has been explored in three previous studies of entrainment effects on mostly European fish species (Lagarrigue, 2013; Lagarrigue & Frey, 2010; Lagarrigue, Voegtle, & Lascaux, 2008). In these studies mortalities were found to occur at low rates with the most recent tests by Lagarrigue in 2013 finding lower rates of mortality than earlier generations of the turbine. To date, only a small number of European fish species have been examined, with none representative of North American non-salmonids species. In addition to this, there was no investigation of the risk of entrainment occurrences by tracking fish upstream from the turbines. This gap in knowledge coupled with the interest in wider implementation of the turbines provides the impetus for this study.

The purpose of this study was (1) determine the likelihood of entrainment for resident fish upstream of the turbine and (2) examine the physical effects on fish that were experimentally entrained in the turbine. The results of these two parts of this study would inform overall risk to fish posed by these turbines so that water resource managers would be able to mitigate injury or otherwise decide whether to implement this turbine.

Chapter 2 - Interactions of a temperate North American fish community with a very low head hydropower facility in Ontario, Canada

Abstract

Efforts are underway to re-evaluate the use of existing instream infrastructure (e.g., weirs, water control dams) for the purposes of hydroelectric generation, with new very low head turbine technology that is purportedly “fish friendly” making retrofitting a viable option. This is the case at Wasdell Falls on the Severn River, ON, Canada, where the first very low head (VLH) turbines in Canada were put into operation at a long-standing dam site. There is lack of information regarding fish usage of areas upstream from these structures and how this can relate to entrainment risk. Therefore, I initiated a study to assess the potential for fish to interact with instream infrastructure and the VLH turbines. Specifically, I assessed risk of entrainment based on fish use of the forebay areas upstream from the infrastructure, including the forebay of 3 operating VLH turbines. Acoustic telemetry was used to determine movements and entrainment events of eight fish species including smallmouth bass (*Micropterus dolomieu*), largemouth bass (Micropterus salmoides), rock bass (*Ambloplites rupestris*), walleye (*Sander vitreus*), northern pike (*Esox lucius*), channel catfish (*Ictalurus punctatus*), white sucker (*Catastomus commersoni*) and pumpkinseed (*Lepomis gibbosus*). Entrainment through the VLH turbines did not occur over the course of one year. Forebay use was exclusive to rock bass, smallmouth bass, northern pike and largemouth bass. When near the dam, fish across the aforementioned species tended to select deeper forebay areas located in front of the flood control dam on site and away from the VLH forebay. Fish use of the VLH forebay was limited to brief forays indicating exploratory movements rather than prolonged residence. The findings suggest that entrainment risk at this VLH turbine site is low for the species and life stages studied.

1 | Introduction

Hydroelectric generation is one of the more common forms of power generation globally. Conventional hydropower has historically made use of high head dams with large storage reservoirs on large rivers. These dams have large physical footprints and often result in massive changes in riverine conditions as a result of reservoir creation, habitat fragmentation and alterations in downstream flow. (Morita & Yamamoto, 2002; Sabater, 2008). There are many more small to medium sized rivers with opportunities to install hydroelectric turbines that are efficient at lower head height and require less storage, thus having the potential to lessen the environmental consequences and increase the potential for developing hydropower facilities on more smaller, lower-gradient systems.

A relatively recent addition to the current array of low-head turbine technologies is that of the Very Low Head (hereafter referred to as “VLH turbines”). This type of turbine was developed by MJ2 Technologies of France and can operate at a very low head of 1.4-4.2m, flow rates of which meet US Department of Energy fish friendliness guidelines (Odeh, 1999), and overall conditions approaching run of the river (Fraser & Deschênes, 2007; Kemp et al., 2014). These fish friendliness guidelines are a set of parameters identified for turbines as the limit at which there is minimal risk to the condition of fish which may become entrained through the turbines (Odeh, 1999). The ability for this type of turbine to make use of very low head sites has drawn much interest and the potential for this turbine to be set up on existing infrastructure allows for reduced installation costs in comparison to conventional turbines (Fernando & Rival, 2014; Fraser & Deschênes, 2007). Furthermore, the amount of material needed in construction at low head sites is far less than would be needed for a conventional turbine. As a result, the forebays of these turbines are quite different. Most notably, there is no large reservoir inherent to high head generating operations. Thus, previous studies on forebay usage by fish are not as applicable to forebay usage in facilities which cause minimal disruptions to natural flow.

VLH turbines have been installed at multiple sites in Europe but have yet to be implemented widely in North America. The features of this type of turbine coupled with the approximately 80,000 potential low head sites in North America, create much potential for this turbine technology (Kemp et al., 2014). Yet, questions remain regarding the environmental impacts of these facilities. These VLH turbines have been tested for direct impacts on fish resulting from entrainment (the voluntary or involuntary passage of fish through a turbine) on a number of European fish species and some North American *Salmonids* with encouraging results (Lagarrigue, 2013; Lagarrigue & Frey, 2010; Lagarrigue et al., 2008), with low rates of mortality found on the earlier studies and a complete lack of mortality on later studies of newer generations of the VLH turbines. Indeed, it is for these reasons that some have labelled VLH turbines as being “fish friendly”. However, none of these studies assessed fish movements upstream as a risk factor. Recently the first VLH turbines in North America were put into operation at Wasdell Falls on the Severn River in Ontario, Canada (Kemp et al., 2014). The site is representative of many potential low head sites with a pre-existing water level control dam that is situated on one side of the river with the VLH turbines on the other.

To achieve a better understanding of the risk of entrainment through the VLH Turbines I carried out a study of the movement of the fish community upstream from the infrastructure complex using acoustic telemetry. My primary goal was to characterize the entrainment risk to different fish species across multiple seasons. My secondary goal was to characterize fish usage of the area upstream from the infrastructure. To achieve these goals, I implanted acoustic telemetry transmitters in eight different fish species and tracked their movements over ~ 1-year period. Most of the previous studies of VLH technology have focused on the consequences of entrainment rather that the likelihood of entrainment. Entrainment risk for resident fish populations is an important metric in understanding the potential ecological consequences of hydropower development (Harrison et al., 2019). Given the lack of research on this topic in small to middle sized rivers with low head dams, this research addresses an important gap in VLH turbine risk assessment and more broadly in fish-hydropower interactions.

Due to the bathymetry, and habitat within the forebay areas and the long time period in which there has been a barrier at this site, it is likely that fish usage of this area will be limited in comparison to further upstream. Furthermore, within the forebay areas, the control dam forebay would likely see more use than the VLH forebay or the area further upstream due to the greater depth and structures providing cover. Also, while usage was predicted to be low, I had hypothesized that some tagged fish would become entrained through the VLH turbine but that this would be based on relative abundance not necessarily behaviourally driven movements of a single species. This is due to the fact that none of the tagged fish

2 | Methods

2.1 | Study site

This experiment was carried out at Wasdell Falls, Ontario (44.780804, -79.293895). This site supports 3 VLH Turbines and is the location of the first operational VLH turbines in North America. Located on the Severn River, these VLH turbines were put in place making use of pre-existing infrastructure to provide sufficient head. The infrastructure currently at the site is composed of a flood control dam on the east side and the trio of Very Low Head Turbines on the west side of the central island. This site has previously supported two other hydroelectric generating ventures over the past century. The three VLH turbines are 3rd generation VLH model 4000s which can be independently operated. The river both upstream and downstream has many cottages and thus receives increased recreational activity during the summer.

In terms of habitat, the area within the VLH and water control dam forebays are deeper (Figure 2-1.) with the pre-forebay area across the entire channel becoming shallower. The forebays themselves are devoid of woody debris and have low macrophyte abundance but do provide eddies on the sides with reduced current. The substrate in the VLH forebay is mostly bedrock with some cobble, while on the water control dam forebay the substrate is mostly cobble with a few boulders. On the upstream side of the infrastructure the banks on the east side have docks which provide shade and cover, and the substrate is mostly bedrock and cobble. While on the west bank upstream of the infrastructure the shore is composed of roots and fine sediment with woody debris. This west bank has a large low lying marshy riparian zone with no tree cover while the east bank is largely treed.

2.2 | Fish capture and tagging

Fish capture was carried out through a combination of boat electrofishing and angling within 3km upstream from the study site. All fish received and external identification marker (anchor tag or fin clip) and an acoustic telemetry tag. Anchor tags were used for larger individuals and fin clips of the pectoral fins for smaller individuals. We tagged all fish of adequate size to support an acoustic tag following a threshold of tag to fish ratio accounting for <1.5% of the mass of the fish. (Brown, Cooke, Anderson, & McKinley, 1999). As a result of the tagging efforts we tagged 8 different species between June 14th and July 25th, 2017. Tagged fish were released at the site of capture at various points within the 3 km range.

The acoustic telemetry tags used were in the form of Lotek Juvenile Salmonid Acoustic Telemetry System tags (JSATS). Surgeries were carried out on the water shortly after capture with fish immobilized using electro-immobilization gloves. These tags were surgically implanted into the abdominal cavity of the fish and the incisions were sutured using Ethicon© PDS® II sutures using the methods outlined in Veilleux et al., (2018). All fish tagged were captured and released upstream from the turbines. The JSATS used were of models SR626 (used for smaller fishes of 73.3 g or heavier) with a weight of 1.1 g, with a battery life of 341 days and SR48 (used for larger fishes of 233.3 g or heavier) with a weight of 3.5g , and a battery life of 914 days.

A total of 138 fish were tagged (Table 2-1) with species including smallmouth bass (*Micropterus dolomieu*), largemouth bass (Micropterus salmoides), rock bass (*Ambloplites rupestris*), walleye (*Sander vitreus*), northern pike (*Esox lucius*), channel catfish (*Ictalurus punctatus*), white sucker (*Catastomus commersoni*) and pumpkinseed (*Lepomis gibbosus*).

2.3 | Acoustic telemetry array

Tagged fish were tracked with an acoustic telemetry array (Figure 2-2) set both upstream and downstream from the infrastructure of the study site at Wasdell Falls, and in place from the spring of 2017 to the fall of 2018. The acoustic telemetry array was composed of 24 Lotek model WHS 4200 receivers distributed over an approximately 6 km river distance (3 km upstream and 3 km downstream of the VLH Turbine site). These 24 receivers were deployed and downloaded multiple times over the duration of the study, and some were redeployed at different locations (thus resulting in a total of 26 different stations). There was a much higher density of stations upstream, and in particular in the forebays of the water control dam and the VLH Turbines, so that we could determine fish movements in this area with greater certainty.

Detection efficiencies were calculated through linear deployment of tags leading away from two representative receivers with detection efficiencies at their highest within a 15m radius of the receivers.

The receivers in the array were secured to ropes connected to floats and cinder blocks to hold the receiver vertically within the water column. The cinder blocks were then tethered to shore using stainless steel aircraft cable.

2.4 | Data filtering and analysis

Filtering and analysis of acoustic telemetry data were carried out in R version 3.6.0. (R Core Team, 2019). Multiple filtering methods were used to remove false detections which are common with this form of technology. Initially the data were filtered using the 10 second burst rate and detection times to separate detection sequences in strings of 10 second intervals from false detections (which would not have constant 10 second intervals). From here the data was filtered by number of detections per timeframe; the threshold for this was 2 detections within 3600 seconds of each other. Finally, a conditional filter was applied which removed any remaining false detections based on fish passage to the section of the river downstream from the study site. This was done to filter any false detections which may have passed the other filters. Filtering the data brought the total number of detections from ~1.5 million, down to ~400,000 detections. After filtering the data, receiver stations were grouped to aid in identification of broader areas of movement. The array in the area immediately upstream from the infrastructure was subdivided into station groups. These included the stations within the forebays of the VLH turbines and water control dam, as well as the grouping of stations in the area immediately upstream from the forebays (Figure 2-2B). Using R, the cumulative average residency time in minutes per individual within each station group was calculated. (Figure 2-4). This was done by multiplying raw detections within each group by 10 (per 10 second burst rate) to obtain seconds of residency. This was then divided by 60 to obtain minutes and then divided by number of individuals of each species (Figure 2-3) detected in each respective forebay area. In addition, abacus and bubble plots were created through the GLATOS R package (Holbrook, Hayden, Binder, Pye, & Nunes, 2019) to aid in visualizing fish movements over the duration of the study (Figures 2-5 and 2-6).

Chi-squared tests were run using Microsoft Excel's "chitest" function on contingency tables. The first test table being composed of the number of individuals (Figure 2-3), of the four species detected in the forebay area (rock bass, smallmouth bass, largemouth bass and northern pike) with the overall number of fish tagged to determine whether relative proportions of species detected in each area of the forebays were statistically similar to each other. A second chi-squared test was run on these proportions but including the relative proportions of the overall number of fish tagged. A chi-squared test was also run on a contingency table of the average cumulative minutes per individual fish within each forebay group and species.

3 | Results

Of the 138 fish tagged we found that none of the fish moved downstream via the VLH. We did find that 5 fish were detected at various points downstream from the infrastructure. Three fish were last detected at the flood control dam forebay before being detected downstream. These fish were of 3 different species: largemouth bass (*Micropterus salmoides*), rock bass (*Ambloplites rupestris*), and smallmouth bass (*Micropterus dolomieu*). The other two fish (of the 5 detected downstream) took undetermined routes possibly from further upstream; these fish were a rock bass and a smallmouth bass. These movements were identified through visual identification of detections in the filtered data.

Of the tagged fish, northern pike (*Esox lucius*), smallmouth bass, rock bass and largemouth bass were detected within the water control dam forebay area and in the VLH forebay. These were the same species detected in the pre-forebay area throughout the summer to fall of 2017. Of these species, rock bass and smallmouth bass had the highest number of detections. Proportionally largemouth bass and northern pike made up a larger number of the fish detected in the forebay areas than the relative frequency in which they were tagged (Table 2-2).

A chi-squared test was carried out between the proportions of individuals detected of each species in each forebay grouping (Table 2-3) resulting in a p-value of 0.996. Thus, indicating that the proportions (relative frequency of the number of individuals of each species) were similar to each other within species groups across all of the forebay areas. This points to individuals of a species entering the forebay area at frequencies similar to overall abundance in our tagged sample size. A chi-squared test was run on the proportions of individuals across all forebay areas and the original total sample of fish tagged. This test resulted in a p-value of 0.573 indicating that the species proportions in the forebay areas followed the same proportions seen in the overall sample of fish tagged.

The final chi-squared test examined the average cumulative time spent in each forebay station group per individual across species. Here the control dam had higher average times spent by the four species than the other two forebay areas. This was confirmed by a chi-squared test on average times across all species and forebay station groupings which resulted in a p-value of <0.001 showing that there was a significant difference between average cumulative residency times across species.

In terms of seasonal use of the forebay area, rock bass were detected on the VLH and pre-forebay station groups (Figure 2-2B) between June and late October 2017. While on the flood control dam forebay they were detected up till November 2017. Largemouth bass were detected in the VLH and pre-forebay station groups from July to mid-September, and later until the end of October in the flood control dam forebay. Smallmouth bass were detected at all three station groups between late August and late October 2017. Northern pike were detected in a more limited timeframe of eight days in September 2017 for the flood control and pre-forebay groups. While in the VLH forebay, northern pike detections occurred over the span of a single day in September. There were isolated detections of rock bass and smallmouth bass in the VLH forebay during the winter (December 5th, 2017 and February 20th, 2018) but beyond these data, there were no more detections of any fish within the forebay areas. However, fish were detected upstream from the forebay up until late August 2018.

Through an examination of cumulative residency time averaged per species and the number of individuals detected (Figures 2-3 and 2-4) I found that rock bass tended to stay for much longer periods in the control dam forebay, but that there were not as many individual fish detected. The smallmouth bass tended to enter the three areas but had low residency times reflected in the number of detections.

4 | Discussion

With the growing interest in wider usage of the Very Low Head turbines, water resource managers require a knowledge of the risk posed by this technology to the fish communities on their respective waterways. Determining likelihood of entrainment is a critical component of a comprehensive assessment of risk on the local fish community. In addition to this, low head turbines in general have very different forebays than conventional turbines. As a result, studies regarding fish movements in these conditions are limited. Research specifically on the risk of entrainment in VLH turbines has not been carried out previously. In conducting this study, we have been able to investigate the two main goals regarding the determination of likelihood of entrainment and characterizing fish movements upstream.

4.1 | Fish Passage

While there has been much research on the entrainment of migratory fishes, resident fish that make use of habitat upstream of hydroelectric infrastructure have the possibility of becoming entrained (Coutant & Whitney, 2000). Juvenile resident fish are most at risk of entrainment due to lower sustained swim speeds but generally have low impacts on the populations of their respective species. Conversely, entrainment of resident fishes can have population level impacts if fecund adult females are entrained (Martins et al., 2014). Entrainment of non-salmonids often occurs episodically as schools of fish become entrained after coming near infrastructure (Martins et al., 2014).

Contrary to my prediction that there would be a small amount of fish movement through the turbines, passage of the tagged fish through the VLH turbines did not occur throughout this study, supporting the idea that the risk of entrainment through the VLH turbines is extremely low. Five tagged fish were detected downstream, none of which appeared to pass through the turbines. Of the five fish, three were last detected on the flood control dam forebay before being detected downstream (the other two fish were last detected further upstream thus indicating that they had moved downstream by another route as they were not detected within the rest of the upstream array). There is connectivity of the upstream and downstream sections via a longer 11 km route which has a lock on it. Since there is a large amount of recreational fishing in this section of the river it is also possible that the movements of these two fish occurred via livewell transfers. Regardless of the route, it is very likely that it was not via the VLH turbine as the forebay is well shielded and telemetry receiver detection ranges well overlap in this area. The reasons for the lack of entrainment are likely due to factors inherent to the design of the VLH series of turbines, especially that of the low draw speed. This combined with the fact that the tagged fish species have maximum sustained swimming speeds (U_{crit}) that are greater than the draw of the turbine. In addition to this, the burst swim speeds are much higher than the U_{crit} of each species (Peake, 2008). For the centrachid species used in this study, smallmouth bass have U_{crit} values ranging from 65 to 98 $cm \cdot s^{-1}$ (Peake, 2004a), largemouth bass from 30 to 50 $cm \cdot s^{-1}$ (Crans, Pranckevicius, & Scott, 2015; Farlinger & Beamish, 1977). Rock bass have U_{crit} values ranging from 18 to 31 $cm \cdot s^{-1}$. Adult northern pike of 42 – 62 cm have U_{crit} ranging from 38.3 - 47.4 cm/s^{-1} (Jones, Kiceniuk, & Bamford, 1974). The intake flow of the turbines in standard operation ranges from 3 to 21 $cm \cdot s^{-1}$ (Site Operator, personal communication, June 30, 2019). When measured on-site (July 21st 2017) flows at 1 m depth from the surface ranged from 0.33 $m \cdot s^{-1}$ to 0.89 $m \cdot s^{-1}$, whereas at the surface flows ranged from 0.17 $m \cdot s^{-1}$ to 0.72 $m \cdot s^{-1}$. These measurements were taken at the trash rack on the upstream side of the walkway over the turbines. These values are below the majority of the U_{crit} values listed here and the lack of fish being entrained points to fish being able to avoid entrainment during seasonally higher flow events. It should be noted that during the study period I observed juvenile smallmouth bass schooling immediately ahead of the turbine and holding in the current. (Personal observation, June 2018).

Fish passage events downstream via the flood control dam were limited. There were number of factors which could have impacted these passage events. Fish usage of this forebay was greater than that of the VLH forebay (Figure 2-4), as a result fish would have a higher chance of movement downstream via this infrastructure simply due to longer durations of presence in the vicinity. Some may have passed the instream barriers of their own volition, or possibly after death. For example, if the fish was dead and floating downstream on the surface it may have drifted over the flood control dam side of the infrastructure. This would be difficult to accurately determine using acoustic telemetry as detections will occur if the fish remained within the detection radius of a receiver, regardless of its condition

4.2 | Forebay Usage

Out of the eight different species tagged over the course of this study only four were detected within the forebay areas immediately upstream from the infrastructure at Wasdell Falls

(Figures 2-5 and 2-6). Of the station groupings upstream of the infrastructure, the flood control dam forebay seems to experience the most use across most of the species detected in the immediate area of the infrastructure (Figures. 2-3 and 2-4). In viewing the average cumulative residency time per species (Figure 2-4), one can see that the control dam grouping has the most cumulative time of detections for rock bass and northern pike, relative to the other areas. Largemouth bass have a higher average cumulative residency time in the pre-forebay area, while smallmouth bass have larger residency times across both the control dam and VLH forebays. The area of the control dam forebay area is deeper and has more cover (in the form of docks) than the other two areas upstream of the infrastructure. Furthermore, the main channel of the river seems to naturally feed into this area while still maintaining the depth seen further upstream. Largemouth bass seemed to use the flood control dam forebay more so than habitats upstream (Figure. 2-5C). From the filtered telemetry data (Figure. 2-6) I could not see any movements of walleye, white sucker or channel catfish anywhere near the forebay area. White sucker and walleye were species that would be expected to be seen in the forebay area even in a limited fashion during downstream spawning movements. (Bellgraph, Guy, Gardner, & Leathe, 2008; Doherty, Curry, & Munkittrick, 2004). These fish were captured further upstream and I did not catch these species in the immediate vicinity of the forebays.

The species detected in the forebay area were present at statistically similar proportions to the overall numbers of each species tagged. As a result, it is likely that that the species detected were related to their overall abundance in the waterway. However, factors including home ranges relative to capture location and habitat type available in the river likely have a large role in the fish movements that were observed (Minns, 1995).

Fish usage of the flood control dam also seemed to occur for a longer duration (from summer to late fall) and across all species detected in the forebay areas. This seems to indicate a seasonal propensity during the summer across all four species for movements into the VLH and pre-forebay areas. As the summer progresses and changes into the fall the fish seem to prefer the deeper areas found in the flood control dam forebay, presumably for increased thermal stability in comparison to the shallows. After early February 2018 there was a lack of detections of any fish within the forebay areas which is indicative of overwintering elsewhere. However, since the acoustic telemetry array was active through to the fall of 2018 is unusual that I did not find any further detections in the forebay areas into the spring and summer of 2018, while there continued to be detections further upstream.

Fish usage of the forebay areas appears to be lesser in most species compared to the rest of the upstream sections (with the exception of largemouth bass). Brief movements into the forebay areas could be the result of fish foraging for prey (Martins et al., 2013). Habitat quality and quantity seem to be the most apparent differing factors which would affect fish use of the forebay areas. The habitat in the area immediately upstream of the turbines is lacking in structure and other habitat characteristics which could be attractive to fish, including macrophytes, deeper portions, woody debris and boulders (Todd & Rabeni, 1989). Unlike conventional hydroelectric facilities which may have a larger reservoir upstream, there is no great increase in depth at the forebay to the turbines. Attempts at electrofishing and angling in the area were relatively unsuccessful in comparison to further upstream (Personal observation, Summer 2017). Furthermore, all species seemed to not spend extended periods in these forebays in comparison to areas further upstream (Figures 2-6 and 2-7). However, fish usage of the forebays could also be explained as a function of home range affinity of individuals and each species as a whole. Smaller home ranges would account for the fish captured and released upstream which were not often detected at the forebay areas. In general, riverine fishes tend to have smaller home ranges than those which live in lacustrine environments, and home ranges generally tend to increase with body size (Minns, 1995). As a result of these factors smaller species like rockbass caught in the vicinity of Wasdell Falls likely would not move very far. More fish were captured upstream sections of the river 2-3km upstream from the site, therefore home range would explain the detection rates of the fish found in the forebay areas. Channel catfish and walleye were only captured and released at the furthest range of the study area at ~3km distance from Wasdell Falls. These species were not detected at all in the areas near the infrastructure at the study site.

Conclusions

The results indicate that (1) entrainment through the VLH Turbines of any tagged fish did not occur; (2) fish movements into the forebay area from upstream were limited; and (3) of the forebay areas the control dam forebay experienced the highest amount of use. Since no tagged fish went through the VLH Turbines, and forebay usage is limited to those fish resident to the vicinity of the forebay, the risk of entrainment to the fish community at this site is low. Future investigations could be carried out at different sites to look at other species and their interactions with low head infrastructure. The layout of the areas around these turbines is variable from site to site, as a result other sites may experience more fish usage of forebay areas or species-specific entrainments. There are still issues associated with fish movement with regards to the VLH turbine sites acting as a barrier to movement. However, this site has had a structure existing here for the past century which makes separation of habitat fragmentation caused by the natural bathymetry and historic anthropogenic changes from the actual turbine difficult. Juveniles of the species used here may be another good point of investigation as they tend to have sustained swim speeds much lower than the adults due to size and less developed musculature and should therefore be more vulnerable to entrainment. In this investigation it was found that the study objectives regarding low entrainment rates and lack of species-specific entrainment were supported. In addition to this I found that movements in the forebays were restricted to half of the species that I surveyed in the 3km stretch upstream with differing area usage by species. While the results of this study may not be extrapolated to forebay usage in all low head sites due to variability, these results do provide insight into how usage can differ from forebays at sites supporting conventional (high head) infrastructure. The VLH Turbines continue to show promise in terms of interactions with ichthyofauna, with a lack of entrainment in this north temperate fish community. Future use of this turbine technology in riverine systems with resident fish populations would appear to be a lower risk endeavour than conventional turbines.

Tables

Table 2-1: The numbers of each species and tagged with JSATS (acoustic telemetry tags) in this study of fish movement upstream of the VLH turbines at Wasdell Falls on the Severn River, Canada. The tagging was carried out during in the summer of 2017.

Species	Number tagged	Min length (mm)	Max length (mm)
Smallmouth bass	68	189	397
Rock bass	43	159	228
Largemouth bass	7	211	463
White sucker	6	315	520
Channel catfish	6	292	350
Northern pike	4	475	717
Walleye	3	282	328
Pumpkinseed	1	-	-
Total	**138**		

Table 2-2: The relative frequencies of individual fish tagged (n) and those detected in each of the 3 station groups within the forebay areas upstream from the VLH turbines at Wasdell Falls, Ontario.

	Smallmouth bass	Rock bass	Largemouth bass	Northern pike
Total Tagged (n)	0.56	0.35	0.06	0.03
Pre-Forebay Group	0.53	0.27	0.13	0.07
Control Dam Forebay	0.44	0.28	0.22	0.06
VLH Forebay	0.50	0.29	0.14	0.07

Table 2-3: The Chi-Square test parameters run on acoustic telemetry data of the forebay areas upstream of VLH Turbines at Wasdell Falls, Ontario with variables and outputs with degrees of freedom. Significant values are highlighted in pink.

Tested Variables	Df	Significance level	P-value	Bonferroni Corrected P-Value
Mean cumulative time (mins)	6	0.05	<0.001	0.004
Proportion of individuals per species detected	6	0.05	0.996	0.004
Proportion of individuals per species detected including proportions from overall tagged sample	9	0.05	0.573	0.003

Figures

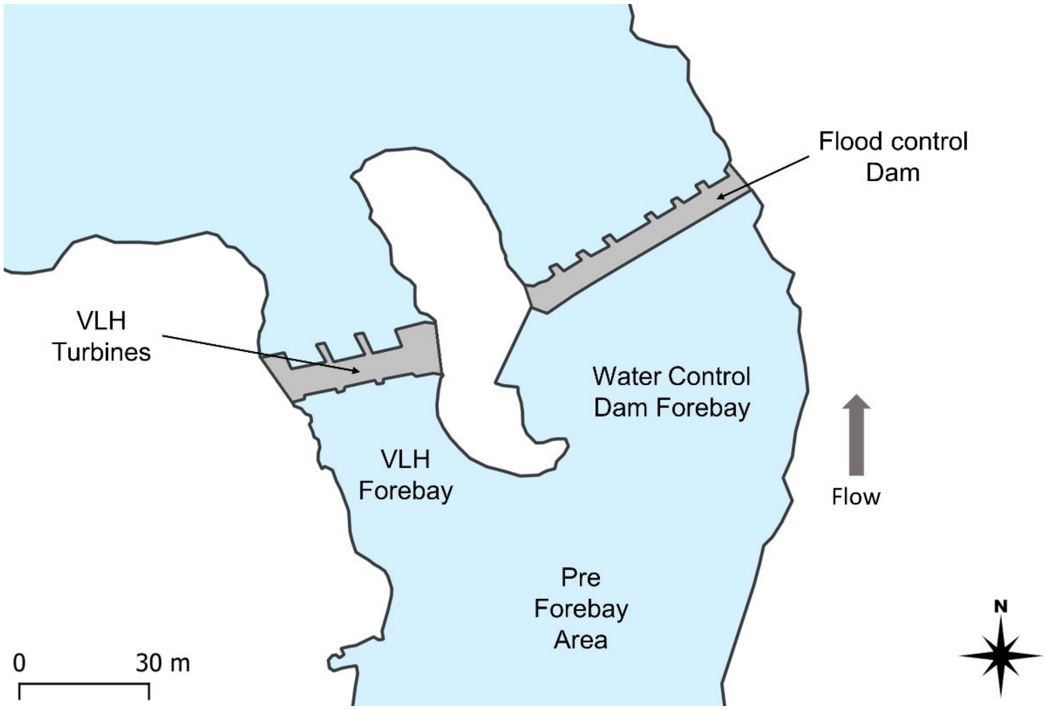

Figure 2-1: The infrastructure located at the study site at Wasdell Falls, on the Severn River: The VLH turbines are west of the central island and the flood control dam is on the east side, (both are shaded in grey) with their respective forebay areas labeled on the upstream side.

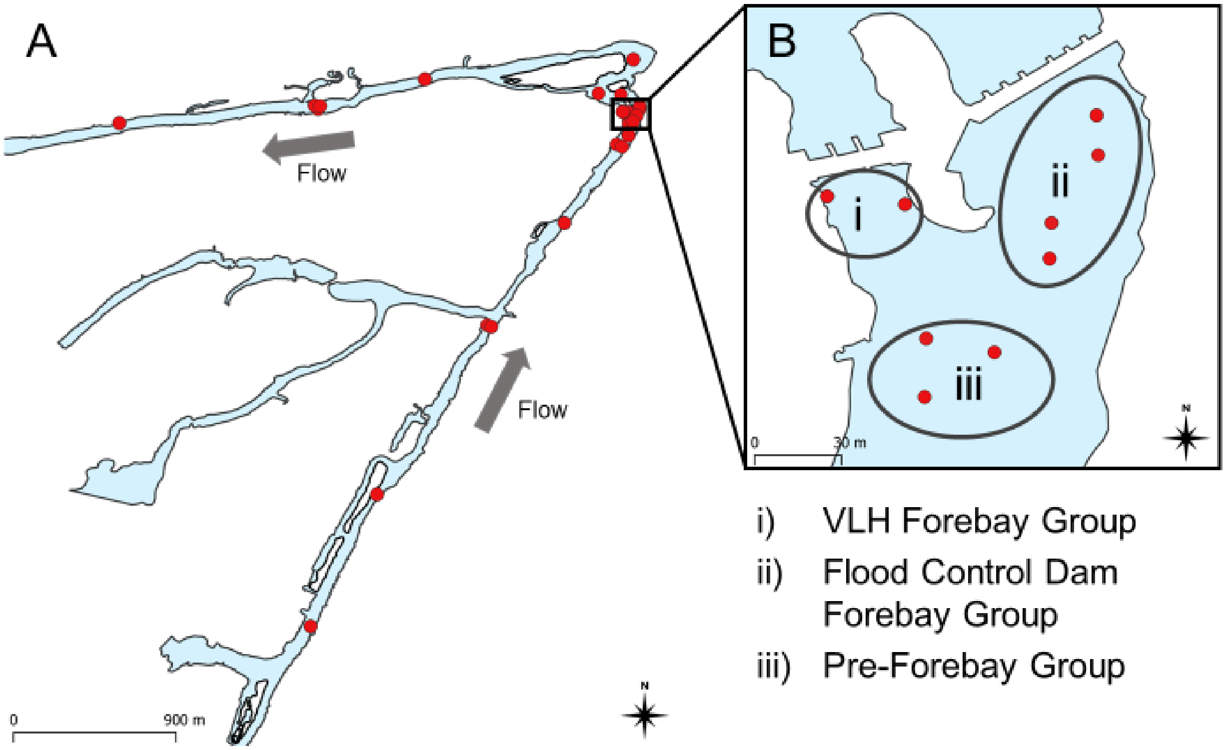

Figure 2-2: A) Locations of stations in the entire acoustic telemetry receiver array on the Severn River (red dots) deployed from summer 2017 to fall 2018. B Closeup of receiver array and station groupings upstream of the VLH turbines at Wasdell Falls. Note that these are stations of deployment and that not all receivers were deployed concurrently.

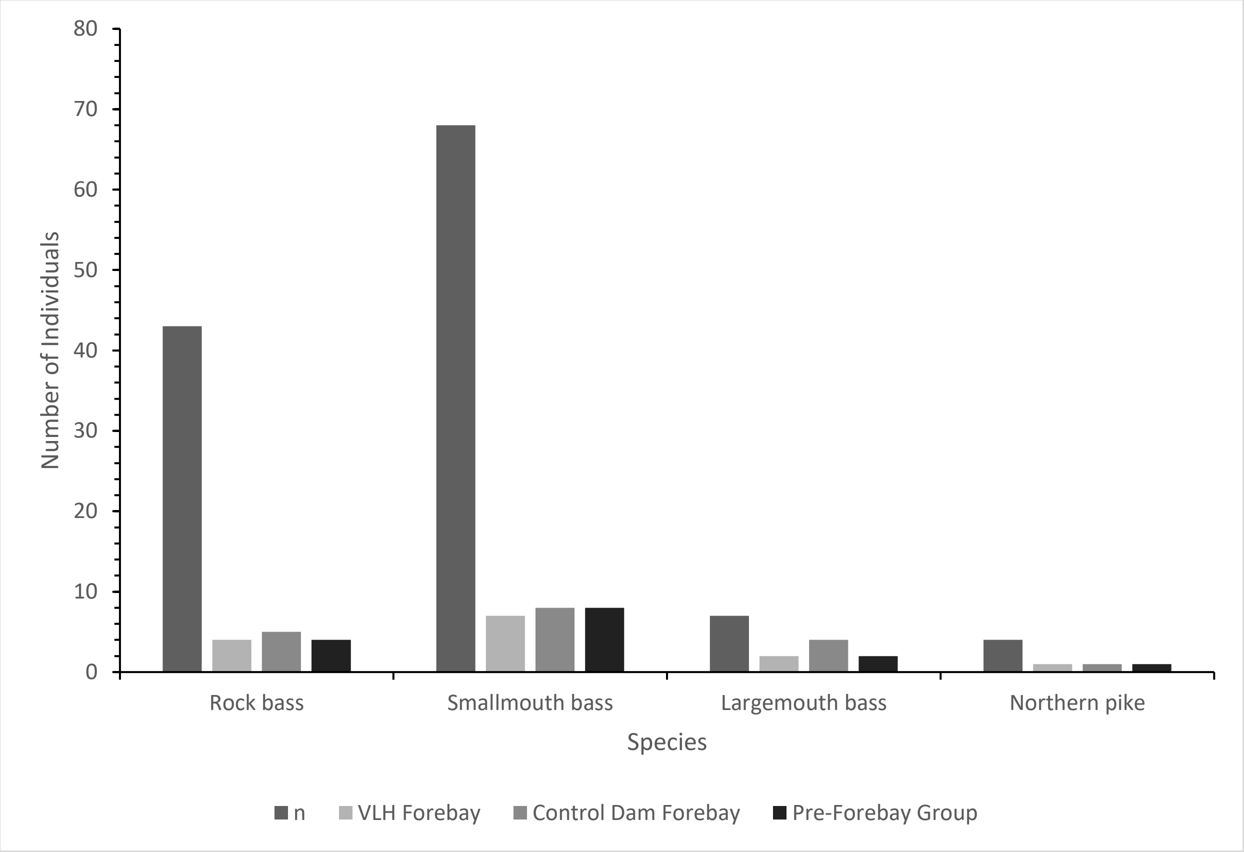

Figure 2-3: The total number of individual fishes of the species detected within the forebay areas at the Wasdell Falls generating complex, in each of the three forebay station groups over the course of the study. The overall number of individuals of each species tagged is represented by (n).

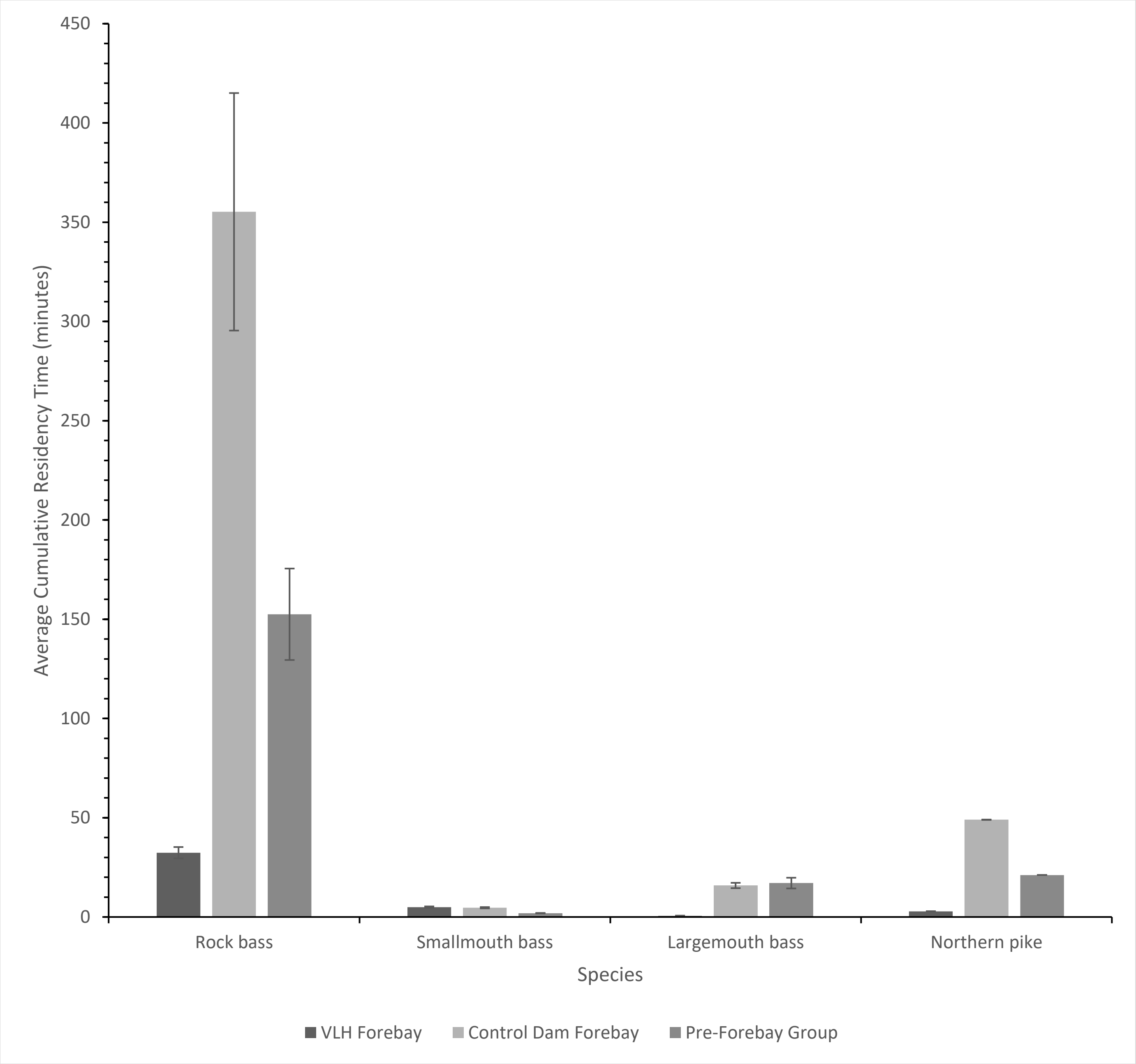

Figure 2-4: The average cumulative residency time (minutes) per individual, species and forebay station group plotted with standard error.

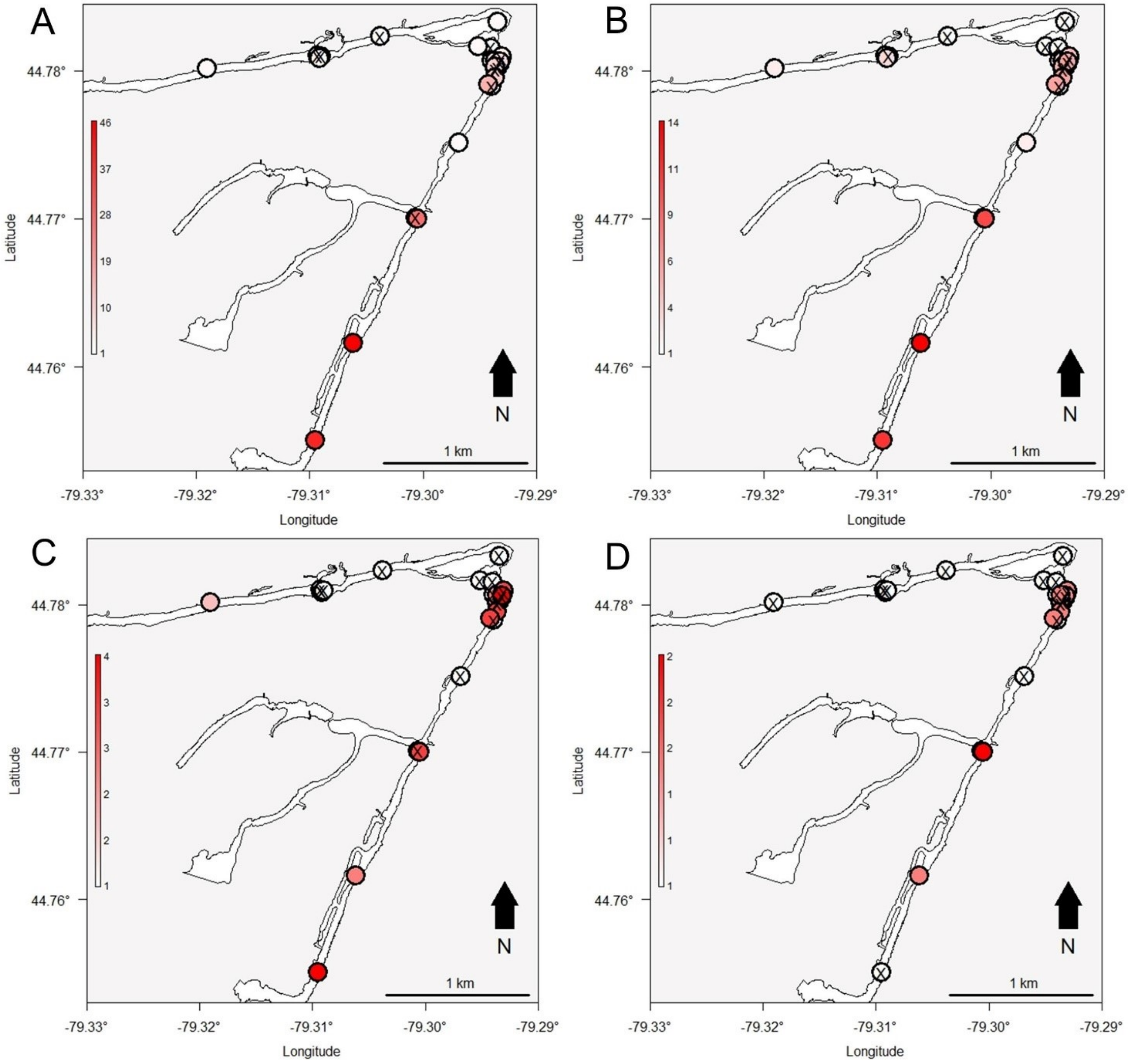

Figure 2-5: Plots of the study area on the Severn River with the VLH site at Wasdell Falls in the upper right of each map. Each plot shows number of detections per station for (A) smallmouth bass, (B) rock bass, (C) largemouth bass, and (D) northern pike. Higher numbers of detections are denoted by a darker bubble shade while a complete lack of detections is denoted by a crossed bubble. Note that in higher station densities crosses may be visible through other stations.

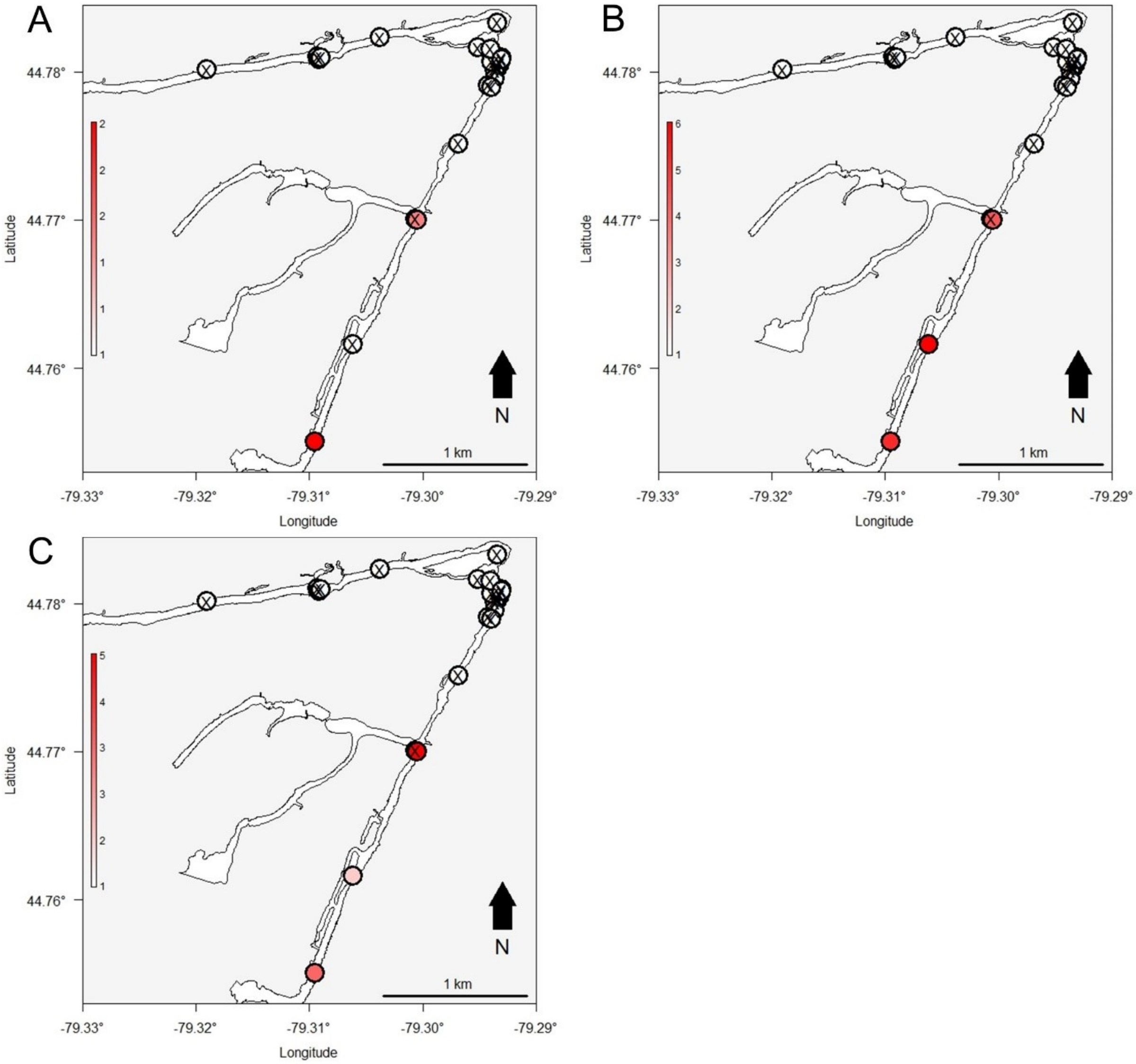

Figure 2-6: Plots of the study area showing number of detections per station for (A) walleye, (B) channel catfish, and (C) white sucker. Higher numbers of detections are denoted by a darker bubble shade while a total lack of detections is denoted by a crossed bubble. Note that in higher station densities crosses may be visible through other stations.

Chapter 3 - Effects of Entrainment Through Very Low Head Turbines on a Representative North American Freshwater Fish Community

Abstract

Very low head (VLH) turbines are a relatively new technology for hydropower generation and are often touted as being “fish friendly” for entrained fish. With growing interest in deploying such technology in north temperate rivers, there is a need for biological assessments to understand how fish of these communities fare in interactions with VLH turbines. I initiated a study to assess the potential biological consequences of VLH turbines entrainment on fish, at the only VLH turbines operating in Canada located on the Severn River, Ontario. Here I assessed risk based on the specific injury and mortality rates resulting from entrainment. To determine turbine specific injury and mortality rates, I experimentally introduced fish into the turbines and subsequently recaptured fish downstream using balloon tags. Research focused on largemouth bass, smallmouth bass, rockbass, walleye and Northern pike spanning body sizes of 17 to 69cm. Using pre-entrainment and post-entrainment assessments I was able to determine injury and mortality incidences. Analysis of the data showed minimal differences between control (no entrainment) and treatment (entrainment) groups. Only one fish (representing 0.6% of total entrained fish of all species and 2.9% of entrained pike) was killed by turbine strike. In general, severe injury occurrences were rare. The most common form of injuries in both control and treatment fish were those related to abrasion (i.e. scale loss, torn fins). These results suggest that entrainment by VLH turbine has negligible effects on the fish species studied here and thus may be a suitable approach for mitigating turbine injury and mortality at low head dams that are common with other turbine types.

1 | Introduction

Hydroelectric generation is one of the oldest and most widespread methods of electricity generation (Sahin, Stewart, Giurco, & Porter, 2017). Most countries with fluvial systems (i.e., rivers) have some form of hydroelectric generating capacity. Harnessing electricity without the need to build mega-dams is regarded as a priority for the hydropower industry with great efforts to develop efficient facilities that can generate electricity on smaller waterways, and do so using existing low head dams or requiring minimal infrastructure investments (Inoue & Shiraishi, 2010). Head height is the difference in distance between intake and outflow at a site. High head is generally defined as being upwards of 100 m while low head is under 30 m (Loots et al., 2015). These smaller waterways which have low heads have historically been overlooked due to efficiency issues with older, conventional turbine designs that require greater pressure to operate. More recently in the history of hydroelectric turbine technologies the development of more efficient turbines capable of operating on a lower head has increased. These low head turbines could provide additional power, making use of the underutilized portion of a country's generating potential, but the benefits in the developing world are possibly greater. (Elbatran et al., 2015; Paish, 2002).

A relatively recent addition to the current limited number of low head turbine technologies is that of the Very Low Head or VLH turbine. This type of turbine was developed by MJ2 Technologies of France to operate efficiently at very low head (1.4m – 3.2m) sites (Fraser & Deschênes, 2007) with flow rates of less than $2m \cdot s^{-1}$, and overall conditions approaching run of the river (Fraser & Deschênes, 2007). The ability for this type of turbine to make use of very low head sites has drawn much interest and the capability of this turbine to be set up on existing infrastructure allows for reduced installation costs in comparison to conventional turbines (Fraser & Deschênes, 2007). As a result, the amount of construction material and investment needed to increase head at low head sites is far less than would be needed for a conventional turbine. Retrofitting infrastructure at existing low head sites also has the benefit of not increasing habitat fragmentation. VLH turbines have been installed at multiple sites in Europe (Kemp et al., 2014). The features of this type of turbine coupled with the 80,000 prospective low head sites in North America create much potential for this turbine technology (Kemp et al., 2014). Yet, questions remain regarding the environmental impacts of these facilities – particularly the consequences of entrainment on fish.

Entrainment through conventional turbines can result in a wide range of different injury types ranging from barotrauma and amputations to scale loss. The causes of these injuries vary, large pressure changes caused by high pressures associated with use of high head (conventional) turbines can cause barotrauma and contact with blades can cause amputations and spinal deflections (Mueller et al., 2017). Otherwise entrainment in conventional turbines can result in bruising, fin tearing, haemorrhaging and numerous other injuries (Hogan, Cada, & Amaral, 2014). These injuries may not immediately have severe impacts on the overall condition of the fish but may make the fish more vulnerable to disease, fungi, parasites, etc. Conventional hydropower differs from the VLH turbine in a number of ways and as a result the VLH turbines operate within parameters that may have less impact on entrained organisms.(Fraser & Deschênes, 2007) The blades of the VLH turbine are much more blunt and in operation the turbine creates lower pressures of 80 kPa/s while the maximum allotted pressure changes to meet fish friendliness guidelines is 550 kPa/s (Fraser & Deschênes, 2007). The VLH turbine uses Kaplan style blades mounted near the surface of the water and on an angle generating electricity through a direct drive system (Lautier et al., 2007). The VLH turbine contains eight blades that can be opened or closed to control the speed of the turbine or completely stop it (Fraser & Deschênes, 2007).

A number of studies have examined the direct impacts of VLH turbine passage on several European fish species and *Salmonids* with encouraging results. Testing of these direct effects of passage was carried out in France on three separate occasions, in 2008, 2010 and in 2013. During testing in 2008, juvenile Atlantic salmon (*Salmo salar*) and European eel (*Anguilla anguilla*) were entrained in a VLH turbine and resulting injuries/mortalities were described (Lagarrigue et al., 2008). This study found a mortality rate of 3.1% with variations in mortality rate depending on the point of introduction into the turbine (i.e. near the periphery, near the hub or mid-blade). A further study on a newer generation of VLH Turbines found no mortality and few injuries among test subjects (Lagarrigue & Frey, 2010). The anguilliform fishes suffered no fatal injuries and very few (2%) individuals suffered any injury. A more recent report from 2013 in France examined entrainment mortality and injury through VLH turbines. This study involved the use of rainbow trout (*Oncorhynchus mykiss*) to mimic native *Salmonids* and *Cyprinids* (tench and common carp) (Lagarrigue, 2013). Here it was found that survival rates varied from 95.6 to 100 percent (Lagarrigue, 2013). Furthermore, this more recent study uses a newer generation of VLH Turbine than the other previous studies as is thus more relevant to future turbine production. All three studies found low mortality and injury rates however there were no species representative of body characteristics seen in North American north temperate fish communities besides the *Salmonids*. Due to differences in the physical traits of species (as would be especially seen between a large number of old world and new world species), the ability to endure entrainment events should also differ across species. Factors like different scale composition and body shape should play a role in this. As a result of the studies in France, the VLH turbines are purported to have minimal entrainment impacts upon fish, however this has never been verified on other North American ichthyofauna with differing traits.

Recently the first VLH turbines in North America were installed at Wasdell Falls on the Severn River in Ontario, Canada (Kemp et al., 2014). The use of VLH turbines at this site and the large number of potential sites are driving interest into wider use of these turbines in North America. This provides the impetus to rectify the lack of knowledge regarding the outcomes of fish entrainment prior to expansion in the number of VLH turbine sites. To achieve a comprehensive assessment of the impacts of entrainment through the VLH Turbines on various fish species, I carried out controlled entrainments and recaptures of various fishes using balloon tags. My primary goal was to characterize mortality rates and the types and severity of injuries resulting from entrainment. In addition to this I wanted to examine differences in impact on a representative north temperate community of North American fish species and determine which body form or species might be most at risk for injury resulting from entrainment within the VLH Turbines. I used five different fish species with body shapes representative of a variety of north temperate fishes. With these species I used a pre-entrainment and post-entrainment assessment of injury to determine injury and direct mortality rates. I had hypothesized that more elongate fish like northern pike would experience increased direct mortality and injury rates in comparison to more gibbous fishes (such as rock bass) and that this would also be reflected in the post entrainment delayed mortality tracking with acoustic telemetry.

2 | Methods

2.1 | Study site

This experiment was carried out at Wasdell Falls, Ontario (44.780804, -79.293895) located on the Severn River. This site supports three VLH Turbines that were installed making use of pre-existing infrastructure to provide sufficient water storage. This site previously supported two other hydroelectric generating ventures over the past century leaving behind a dam that is currently used to regulate water levels. The three turbines (3rd generation, model 4000) can be independently operated. The river both upstream and downstream has many cottages and thus receives increased recreational activity during the summer. The fish community surrounding the site is typical of warm/coolwater fish communities of the area, dominated by *Centrachids*, with *Esocids* and *Percids* following in abundance.

2.2 | Experimental design

To determine the specific injury and mortality rates resulting from entrainment within the VLH turbine I used controlled entrainment and recapture to determine specific injury and mortality levels across 5 different species representing a wide variety of body shapes. These species listed from gibbous to elongate body forms are: rock bass (*Ambloplites rupestris*), smallmouth bass (*Micropterus dolomieu*), largemouth bass (*Micropterus salmoides*), walleye (*Sander vitreus*), and northern pike (*Esox lucius*). Fish were captured for this study through a combination of boat electrofishing and angling.

After the fish were captured, the weight, length, and species were recorded. For the purposes of cataloging injuries and for injury assessment backup, a digital photograph was taken of both sides of the fish. A ruler and gridded background were included in each photo as a reference for scale.

Fish were tagged with two types of internal tags during this study. PIT tags and acoustic telemetry tags were used. The PIT tag was injected into the dorsal musculature of all fish to allow for identification of individuals. A subset of 62 fish were tagged with Lotek© Juvenile Salmonid Acoustic Telemetry System (JSATS) tags. These fish (Table 1-2) were composed of 34 individuals in the treatment group and 28 in the control group.

The purpose of these acoustic tags is to allow us to determine post-entrainment survival rates by observing movements (or lack thereof). These tags worked in conjunction with an acoustic telemetry array of 24 Lotek WHS 4200 receivers located in the river 3 km downstream and 3 km upstream from the study site (Chapter 2). The acoustic tags send out acoustically transmitted signals every 10 seconds which are received and recorded by the receivers. The acoustic tags were surgically implanted in the abdominal cavity of the fish via a small incision which was closed using Ethicon© PDS® II sutures (Veilleux et al., 2018). During this procedure the fish were immobilized with electro-immobilization gloves. After the acoustic tags and PIT tags were implanted, the fish were held in a net pen in the river overnight so that any mortalities resulting from the tagging procedure could be identified.

2.3 | Balloon Tagging

Fish were kept in an aerated holding tank at the VLH site prior to entrainment. Before the application of balloon tags, fish were anesthetized using electro-anesthesia gloves. Balloon tags were used for recapture as they cause minimal external damage to the fish in comparison to other recapture methods. (Boys et al., 2013; Heisey, Mathur, & D'Allesandro, 1993; Skalski, Mathur, & Heisey, 2002). The balloon tags were affixed to the fish by inserting a length of 80lb monofilament fishing line through a large-gauge needle which was itself fed through the dorsal tissue of the fish. Depending on the size of the fish, one or more balloon tags were attached. To achieve a higher recapture success rate, I used a loop through the dorsal tissue so that the line passed through the dorsal tissue twice and carried a balloon on either end of the loop. The balloon tags function by inflating from gases produced as the result of an acid base reaction. In the balloon tags I used six cellulose size 1 capsules filled with reactants in a 2:1 ratio of base to acid. Two of these capsules contained anhydrous oxalic acid ($C_2H_2O_4$) while the other four contained sodium bicarbonate ($NaHCO_3$). Immediately prior to use 7 ml of water were added to the balloons using a syringe after which the activated balloon tag was tied to the loop of monofilament using an overhand knot. The capsules holding the reactants are softened by the water and agitation of passing over or through the turbine breaks open the capsules mixing the reactants.

2.4 | Experimental Entrainment Device

The entrainment device (Figure 3-1) that I used to experimentally entrain the fish through the VLH Turbine was composed of a reinforced flexible 0.2m diameter by 7.6m PVC hose attached to a 681.37L stock tank. The purpose of the stock tank was to provide a sufficient pulse of water behind the fish such that the fish would have been unable to swim back up hose. One end of this hose was held in place directly at the periphery of the turbine through the trash rack at the distributor ring using a steel pole and ropes. The other end of the hose was attached to a watertight PVC gate on the bottom of the stock tank. Attached to the gate on the inside the holding tank, I used a mesh cylinder to hold the fish immediately over the opening to the gate/pipe. The entire interior of the apparatus was constructed with smooth edges to prevent fish from being injured in the apparatus.

The entrainment device operates by having a full stock tank/reservoir with the prepared fish and activated balloon tags held in the mesh positioning cylinder. This ensures that the fish is directly over the opening to the hose when the gate is pulled. When the gate is pulled open, the entire contents of the stock tank (including the fish) rush down the hose. The fish is prevented from being entrained at excessive speed by the presence of standing water in the lower end of the hose which absorbs much of the kinetic energy of the moving water and fish.

The fish in the treatment group were flushed through the turbine at the periphery (opposite to the hub). This treatment was chosen as previous testing found that entrainment at the periphery has the highest occurrences of mortality and injury in comparison to mid blade introductions and introductions near the hub (Lagarrigue, 2013; Lagarrigue & Frey, 2010). I also entrained the fish in the treatment group at 50% blade opening as this was also found to have a higher incidence of injury and mortality in comparison to 75% and 100% blade openings (Lagarrigue, 2013).

2.5 | Recapture and Cataloguing

Upon exiting the entrainment apparatus, the balloon tags began to inflate in a time varying from 9 to 20 minutes depending on water temperature. The inflation of the balloon tags caused the fish to be pulled to the surface at which point the fish was recovered using a dip net by a crew member waiting in the turbine outflow on a boat. Fish within the control group received the same treatment and tagging procedures as above but instead of being entrained in the turbine they were flushed with the hose nozzle at the surface about 1m away from the edge of the crest gate (located at the top of the turbine). Therefore, these control fish experienced the same drop height into the tailrace post flushing but did not encounter the blades of the VLH.

The types of injuries classified by standardized body sections were assigned a score of 0 to 5 following the protocol used by Mueller et al., (2017) This scoring works by assigning higher scores for higher intensities of injuries and lower scores for lesser severities, with 0 being assigned for a lack of injuries in the category. In this scoring system the fish were divided into standardized sections and assessed for different types of injuries. These were visually assessed with the fish being held in an aquarium. Digital photographs were also taken of these fish post entrainment using the same methods outlined above. Immediately after post entrainment assessment was completed, the fish were released below the dam.

2.6 | Data analysis

Analyses involving permutational multivariate analysis of variance (PERMANOVA)s and non-metric multidimensional scaling (NMDS) run using R version 3. 6. 0. The dataset generated by field collection was used to make a fish by fish matrix of Bray-Curtis dissimilarities. From here one-way PERMANOVAs were run on within species groups looking at time (pre-entrainment and post-entrainment) and treatment effects. This test was chosen as it is nonparametric and robust which was needed to function effectively on my data. From here NMDS ordinations were run using the “vegdist” function from the Vegan package for R (Oksanen et al., 2019). NMDS plots were created within control and treatment groups on pre and post retrieval injury scores. The treatment group NMDS had a stress level of 21.0 at two dimensions and the control group had a stress level of 19.5 at two dimensions.

For the Wilxocon signed rank tests, the injury score for each fish were pooled by summation into a single pre retrieval and a single post retrieval condition score. Wilcoxon signed rank tests were run using SPSS version 26.0 (IBM Corp, 2019) within species and treatment groups between pre and post retrieval pooled injury scores. This test was used as my data violated assumptions of many parametric statistical tests.

The data from the fish tagged with acoustic transmitters were imported into R and filtered using the min lag filter from the GLATOS package (Holbrook et al., 2019). The data were also filtered by tag signal rate and a conditional filter to remove other false detections. These false detections are inherent to the noisy environment of the system. From here movements were examined for mortalities.

3 | Results

The majority of injuries observed were abrasion-related with few other injury types observed. In general, patterns of decreasing fish condition post entrainment were also seen in control fish. Throughout this study there were no instances of visible barotrauma from any of the fish. Furthermore, rates of other more serious injuries including spinal deflections and minor body amputations were low. Severe amputation events were even more rare with only one mortality definitively caused by entrainment, in which one Northern pike from the treatment group that was passed through the turbine was recaptured with a partial decapitation (Figure 3-2). This accounts for a direct mortality rate in the overall treatment group across (all species) of 1.16% and of the treatment group of northern pike (16 fish) (Table 3-1) this accounts for a direct mortality rate of 6.25%.

The results from one-way PERMANOVAs within species, pre/post entrainment, between treatment groups (Table 3-3.) show that the difference between injury rates in the control group and treatment group were not significant for rock bass, smallmouth bass and Northern pike. However, there was a significant difference between before and after injuries within the treatment group in for largemouth bass. Nonmetric multidimensional scaling (NMDS) were performed on control (Figure 3-3) and treatment groups (Figure 3-4) for fish condition before and after passage. In the control group NMDS (Figure 3-3) it is evident that rock bass, smallmouth bass and northern pike had injury patterns that overlapped considerably while largemouth bass appeared to have injury patterns that differ from the other three species. However, there are no major spatial changes in these injury patterns between pre and post recovery. In the treatment group NMDS (Figure 3-4A) even greater overlapping in injury patterns across all species in the pre recovery group is evident. However, in the post-recovery group (Figure 3-3B) it seems that largemouth bass injuries post entrainment deviate from those experienced by the other species.

In addition, the Wilcoxon signed ranks test was performed within species and treatment groups between pre and post retrieval groups (Table 3-4). The lack of significance in all but three groups points to little change in fish condition between the pre and post passage groups. However, there was significance in smallmouth bass control and treatment groups, also in the Northern pike treatment group, thus indicating a significant change in condition in these species groups between pre and post passage. The plotted mean condition scores by species and treatment (Figure 3-5) revealed that injury severity did not increase appreciably within treatment groups when considering pre and post retrieval injury evaluations.

For examination of longer term post-entrainment survival, the subset of fish tagged with acoustic tags were monitored until the fall of 2018. A seven-day time threshold was used in which I identified mortalities that occurred after entrainment. I found that one largemouth bass and one smallmouth bass of the treatment group and control group respectively appeared to be dead within this timeframe. The dead largemouth bass accounts for 6.25% of all largemouth bass within the treatment group, while the dead smallmouth bass accounts for 5.56% of all control smallmouth bass.

4 | Discussion

This study was carried out to address the knowledge gap that exists surrounding the effects of entrainment by VLH turbines on north temperate fish species. Due to the potential for widespread use of this type of turbine in North America, testing of entrainment effects on different species beyond those studied in France (Lagarrigue, 2013; Lagarrigue & Frey, 2010; Lagarrigue et al., 2008) has the ability to provide water resource managers with a more complete understanding of the ecological risk involved with these operations. In this case the physical traits of the fish community present at the study site is representative of a range of fishes found across North America and differ from the species tested in Europe. If specific species are at a greater risk of mortality or certain injury types, steps can be taken to mitigate risk to the fish community (Algera et al., 2019). In my investigation into this matter I was able to identify sublethal and lethal injury rates and compare these measures across the treatment groups.

I had originally hypothesized that more elongate fish would be most vulnerable to mortality from entrainment and since none of the more gibbous fish were affected by spinal deflections or amputations of the body, it seems that this is partially supported. However, while elongate body types may be more vulnerable than others, this should be considered in perspective with the overall low rates of severe injury and extremely low rates of mortality. The most common injuries observed in this study were abrasion related. This group of injuries includes: scale-loss, eye cloudiness, and minor hemorrhaging (Mueller et al., 2017). However, there was a lack of significance in the PERMANOVA tests (Table 3-3) between control and treatment groups in the majority of fish species. This points to the injuries observed occurring as a result of holding and handling which was constant among both groups. Previous studies into injuries resulting from holding in nets, have reported fraying of fins, injury to the mouth and scale loss as common (Colotelo, Cooke, et al., 2013; Colotelo, Raby, et al., 2013). These were the same types of injuries which were seen in the majority of fish used in this study. Overnight holding was necessary to observe specimens for mortalities caused by the tagging procedure and to keep constant holding times across all fish. This made the fish vulnerable to abrasion injuries in the mesh holding pens. The PERMANOVA results identify significance between treatment and control groups in largemouth bass. This is also seen in injury patterns via NMDS plots specifically in (Figure 3-4). This points to largemouth bass being affected more than the other species by entrainment. It is however of note that while the injury patterns may differ significantly, this does not necessarily make the largemouth bass more vulnerable as there were (like with all of the other species) a lack of injuries that would be classified as severe. Otherwise the NMDS plots of the control group (Figure 3-3.) show relatively constant injury patterns. This differs from the treatment group NMDS plot as the injuries remain similar in pattern before and after passage.

The Wilcoxon signed ranks test outputs (Table 3-4) which compared the before and after passage conditions of fish within species and treatment groups. These outputs show significance in three groups: smallmouth bass control and treatment groups, also in the Northern pike treatment group. The significance in both the control and treatment groups of the smallmouth bass point to handling effects as this was the only variable held constant across both groups. Therefore, it is possible that smallmouth bass are more susceptible to injuries resulting from handling and holding. The significance in the Northern pike treatment group is however not paralleled in the control group, however this is likely the result of assessment error as the pike within this group tended to have a better condition post passage than before (Table 3-4).

The lack of marked or easily visible changes in mean injury scores across treatments and fish (Figure 3-5) points to similar mean rates of injury across species and treatment. There is some human error involved in injury evaluation in the field as there are some species and treatments which seem to have improved in condition even post entrainment. This is something that could be addressed in the future by using hatchery fish of excellent condition for future testing to avoid incidences of these errors However, finding these species from aquaculture would be expensive and for some species impossible. Difficulties in determining small changes in fish injury severity when the fish may have multiple initial injuries is the likely culprit in these errors. Visual identification of injuries can be subjective and therefore can vary (Colotelo, Smokorowski, Haxton, & Cooke, 2014).

The VLH turbines operate with maximum pressure changes of 80 kPa/s while the maximum allotted pressure changes to meet fish friendliness guidelines is 550 kPa/s (Fraser & Deschênes, 2007). During the course of this study I observed no instances of barotrauma (commonly resulting from entrainment in conventional turbines) including injuries such as emboli in the eyes or fins, hemorrhages or bulging of the eyes, and anal bleeding. (Čada, 2001; Mueller et al., 2017; Stokesbury & Dadswell, 1991). Since none of these injuries were seen in this study, the purported pressures generated by this type of turbine being much lower than that of conventional hydroelectric turbines (Fraser & Deschênes, 2007) seems to be corroborated in so far as its effects on entrained fish.

The single mortality caused by a catastrophic partial decapitation in a Northern pike (Figure 3-2) seems to parallel injuries caused by grinding or impingement between moving and non-moving structures (Cooke et al., 2011) on the VLH turbine. The most likely possible locations of grinding impingement are between the turbine housing or trash-rack and the blade. This type of injury (decapitation) has been reported as being caused by shear stress in conventional turbines by Stokesbury & Dadswell (1991). However, this is unlikely the case here as the maximum velocity gradient through the shear zones in the VLH turbine are quite low with a maximum of 10 m/s/m (Fraser & Deschênes, 2007). This is especially low considering that the maximum velocity gradient through the shear zones of 180 m/s/m is required under fish friendliness guidelines. (Cooke et al., 2011). Furthermore, since the leading edges of the blades of the VLH turbines are much broader and blunter than other turbines, blade strikes seem to be less likely to result in severing of the fish during entrainment. This measurement of sublethal affects on released fish using acoustic telemetry shows very similar mortality among treatment and control fish. This points to the possibility of overall stress and the large amount of handling involved on both groups playing a role in duress and eventual mortality. I was unable to capture and entrain a large enough number of walleye to run any meaningful statistics, however injury patterns seem to be similar to most other species with no severe injuries observed.

In terms of prior VLH entrainment testing the rates of mortality seem here are lower than those observed in the 2008, and 2010 VLH entrainment tests. (Lagarrigue & Frey, 2010; Lagarrigue et al., 2008). The results here were more similar to what was observed in the most recent tests of VLH entrainment in Europe (Lagarrigue, 2013). This is partially due to the fact that the cause of impingement between the blade ends and the housing was identified in the older designs and the turbine design was updated to rectify this (Lagarrigue & Frey, 2010). Tests of the newest design, which was installed at Wasdell Falls, found that mortality rates ranged from 1.1% to 4.4% depending on the species and at the 50% blade opening and the periphery of the turbine. (Lagarrigue, 2013). In these tests it was also found that for large rainbow trout entrained at the periphery and at 50% blade opening there was a 6.7% mortality rate within 24 hours. The direct mortality rate from this study at Wasdell Falls was below this range, at 6.25% of treatment northern pike. However, in the 2013 tests in France the number of fish across all species which were entrained was larger with 30 large rainbow trout entrained at 50% blade opening at the periphery of the turbine, with the overall number of fish used in the study occurring in the hundreds.

The study by Lagarrigue (2013) observed a species specific delayed mortality rate ranging from 3.45% to 6.7% within 48 hours. However, since there were issues with oxygen related mortality in holding for this project, the results in this study are not directly comparable with those rates of delayed mortality. Furthermore, the handling seemed to be less for the 2013 tests due to the limited detail in which injuries were recorded and the fact that hatchery fish of good condition were used. In contrast, this study at Wasdell Falls had longer periods of injury assessment prior to entrainment due to use of solely wild-caught fishes. Our longer term delayed mortality rate obtained by telemetry was similar to that found by Lagarrigue (2013) at 6.25% of entrained largemouth bass but over a longer period of time (7 days). Our control fish delayed mortality rate within the smallmouth bass group was 5.56% within 7 days. This was in contrast to Lagarrigue who found no immediate or delayed mortality in the larger control fish, however again the fish was monitored for a shorter period of time. The telemetry data allowed us to identify the longer-term delayed mortality of these two fish, but since each fish was of a different treatment group and species it seems that no specific group or species of fish was affected.

The entrainment apparatus worked well and allowed us to overcome the lack of draw which makes experimental entrainment difficult in turbines that operate with such low intake velocities. This low intake velocity of the VLH turbine (Fraser & Deschênes, 2007) means that the mortality rates are further diluted by the fact that all of the species involved should be able to easily escape near entrainment events. This is due to the maximum critical swim speeds of all tested species being well above the normal operating flow into the turbines. Smallmouth bass, largemouth bass, walleye, rock bass and Northern pike all having critical swimming speeds ranging from 18 to 114 $cm \cdot s^{-1}$ (Crans et al., 2015; Farlinger & Beamish, 1977; Jones et al., 1974; Peake, 2004b, 2004a; Peake, McKinley, & Scruton, 2000) while at the turbine, flows range from 3 to 21 $cm \cdot s^{-1}$ (Site Operator, personal communication, June 30, 2019). The flows were measured on-site on July 21st, 2017. Here flows at 1m depth from the surface ranged from $0.33 m \cdot s^{-1}$ to $0.89\ m \cdot s^{-1}$, at the surface flows ranged from $0.17\ m \cdot s^{-1}$ to $0.72\ m \cdot s^{-1}$. These measurements were taken across the coarse trash rack on the upstream side of the walkway on the turbines, with the range due to microhabitat variations in flow across the face of the turbines and were measured on a day when two out of the three turbines were operational.

It is possible that this experimental design could be applied to aid in risk assessments on other low head or low-pressure turbines. The use of balloon tags for recapture proved to be an effective system for examination of sublethal injuries to fishes caused by entrainment. Future studies may benefit from entrainment of a device like a sensor fish (Deng, Carlson, Duncan, & Richmond, 2007) which could provide more detailed profiles of pressures and other parameters experienced by fish during entrainment.

Overall the results of this study support the purported minimal impact upon fishes caused by entrainment within the VLH Turbine. It should also be considered that this experiment has involved entrainment of fish with the worst of the parameters tested in 2013 entrainment study in France acting upon the fish (Lagarrigue, 2013). In these tests entrainment close to the hub and at mid blade had lower mortality rates than the periphery. Also blade openings of 100%, and 75% were found to have lower mortality rates than 50% blade opening. As a result, in many other cases of different operating regimes the fish would likely be impacted less than what was shown here. Even with these variables acting against the tested fish I did not see many of the injuries commonly associated with other conventional hydroelectric turbines. Therefore, the Very Low Head series of turbines continue to show promise with regards to its minimal impact on entrained fishes with physical traits beyond those of European species.

Tables

Table 3-1: Numbers of each species used in the exploration of injury and mortality resulting from entrainment through the VLH turbines at Wasdell Falls, Ontario. Also listed with size and weight ranges and control/treatment breakdown.

Species	Size Range (mm)	Weight Range (kg)	# of Fish (Treatment)	# of Fish (Control)	Total
Rock bass	166 - 263	0.06 - 0.78	21	15	36
Smallmouth bass	160 - 481	0.11 - 1.62	30	18	48
Largemouth bass	183 - 429	0.09 - 1.19	16	13	29
Walleye	303 - 451	0.31 - 0.78	3	1	4
Northern pike	353 - 687	0.23 - 2.96	16	8	24
		Total Fish	86	55	141

Table 3-2: Numbers of each species used in the subset of 62 fish tagged with acoustic tags during testing of injury and mortality resulting from entrainment through the VLH turbines at Wasdell Falls, Ontario.

Species	Treatment	Control
Rock bass	9	4
Smallmouth bass	15	13
Largemouth bass	7	9
Walleye	2	0
Northern pike	1	2
Totals per treatment	34	28

Table 3-3: Output from one-way PERMANOVAs run on raw injury scores found during the entrainment study on the VLH turbines at Wasdell Falls, Ontario, using Bray-Curtis dissimilarities exploring treatment and time effects (and interactions effects) within species groups. Run with 999 permutations, significant values highlighted in red.

Species	Variable	Df	SumsOfSqs	MeanSqs	F.Model	R2	Pr(>F)
A. rupestris	Time	1	0.00826	0.008264	0.66568	0.00929	0.479
	Treatment	1	0.03425	0.03425	2.75873	0.03852	0.11
	Time:Treatment	1	0.00241	0.00241	0.19416	0.00271	0.683
	Residuals	68	0.84422	0.012415	0.94947		
M. dolomieu	Time	1	0.10128	0.101277	7.4399	0.07455	0.004
	Treatment	1	0.00333	0.003334	0.2449	0.00245	0.711
	Time:Treatment	1	0.00147	0.001468	0.1079	0.00108	0.816
	Residuals	92	1.25236	0.013613	0.92191		
M. salmoides	Time	1	0.04184	0.041843	3.0369	0.04765	0.062
	Treatment	1	0.08676	0.086757	6.2965	0.0988	0.007
	Time:Treatment	1	0.0055	0.005496	0.3989	0.00626	0.687
	Residuals	54	0.74404	0.013779	0.84729		
E. lucius	Time	1	0.04134	0.041342	4.7323	0.0898	0.016
	Treatment	1	0.02507	0.025074	2.8702	0.05446	0.063
	Time:Treatment	1	0.00957	0.00957	1.0955	0.02079	0.325
	Residuals	44	0.38439	0.008736	0.83495		

Table 3-4: Output from Wilcoxon signed-ranks tests within species and treatment groups using pooled injury scores of fish used in the entrainment study on the VLH turbines at Wasdell Falls, Ontario. Specifically, between the before vs. after groups. Significant values are highlighted in red.

Species	Group	Z	Asymp. Sig. (2-tailed)
Rock bass	Control	-.255[c]	.799
A. rupestris	Treatment	-1.036[b]	.300
Smallmouth bass	Control	-3.151[b]	.002
M. dolomieu	Treatment	-3.385[b]	.001
Largemouth bass	Control	-1.274[b]	.203
M. salmoides	Treatment	-1.912[b]	.056
Northern pike	Control	-.649[b]	.516
E. lucius	Treatment	-2.933[b]	.003

a. Wilcoxon Signed Ranks Test

b. Based on negative ranks.

c. Based on positive ranks.

Figures

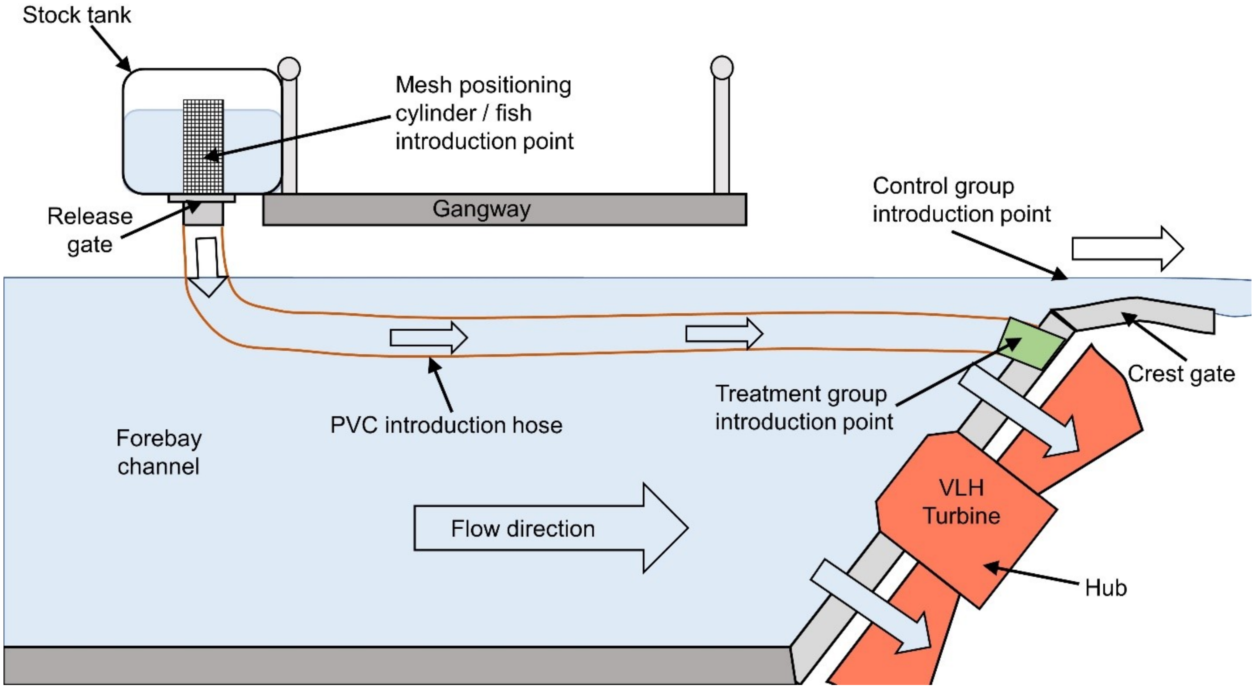

Figure 3-1: Schematic of the experimental entrainment apparatus used to experimentally entrain fish through the VLH turbines at Wasdell Falls, on the Severn River in Canada. The fish rests within the mesh positioning cylinder within the filled stock tank. A pull of the release gate below the stock tank sends the fish and the water down through the hose and through the treatment introduction point (in green) or the control group introduction point above the crest gate.

Figure 3-2: The single direct mortality observed in this study of the effects of entrainment on fishes through the VLH Turbines at Wasdell Falls on the Severn River, Canada. This northern pike experienced a catastrophic partial decapitation.

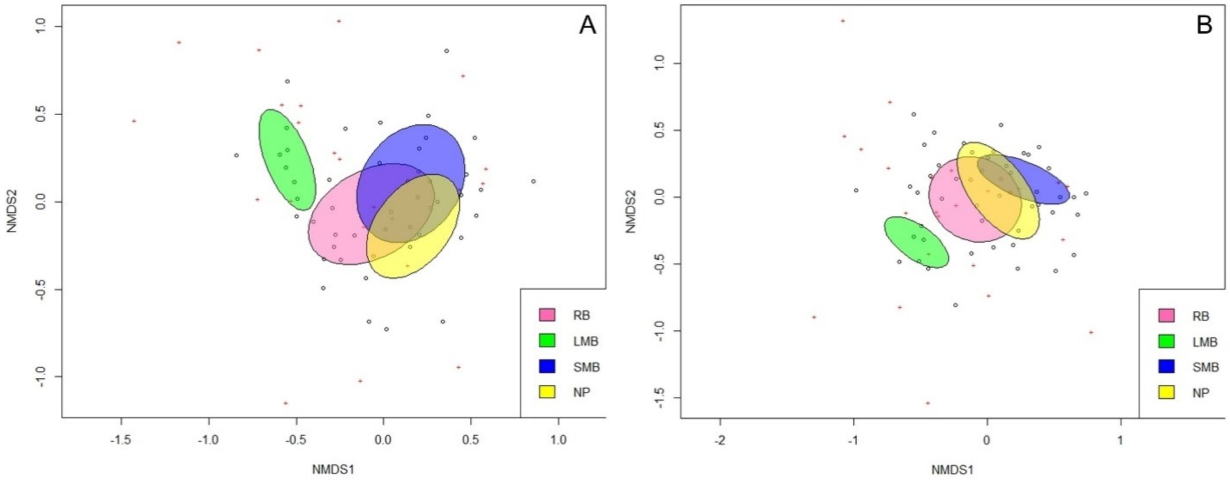

Figure 3-3: NMDS ordinations on fish by fish injury data for the control group before passage over the VLH turbine at Wasdell Falls on the Severn River (A) and after passage (B) by species with NP, LMB, SMB, RB and W representing northern pike, largemouth bass, smallmouth bass, rock bass and walleye respectively.

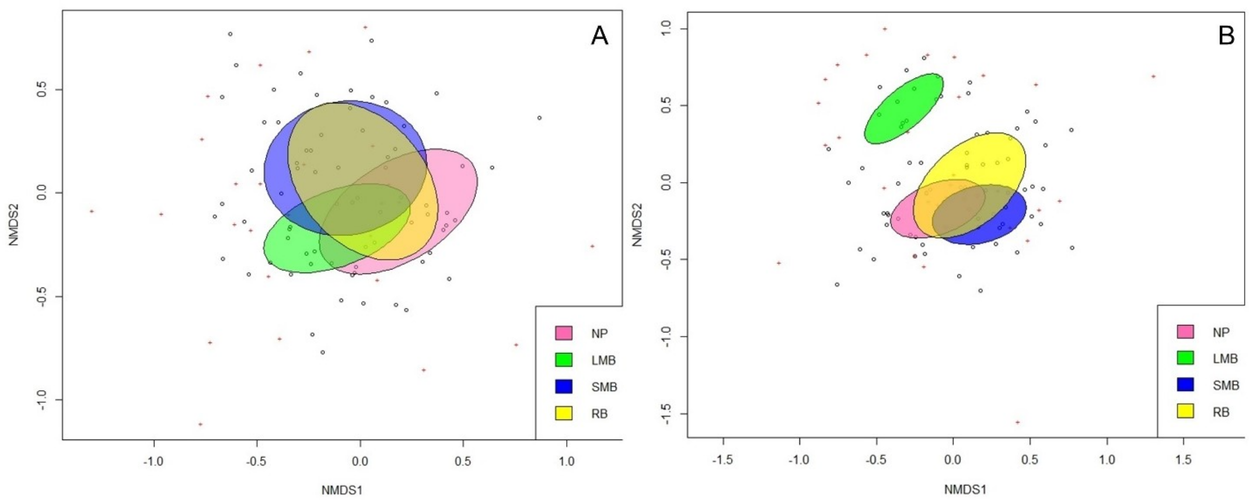

Figure 3-4: NMDS ordinations on fish by fish injury data for the treatment group (entrained at the blade periphery and 50% blade opening) before passage through the VLH turbine at Wasdell Falls on the Severn River (A) and after (B) within the treatment group by species with NP, LMB, SMB, RB and W representing northern pike, largemouth bass, smallmouth bass, rock bass and walleye respectively.

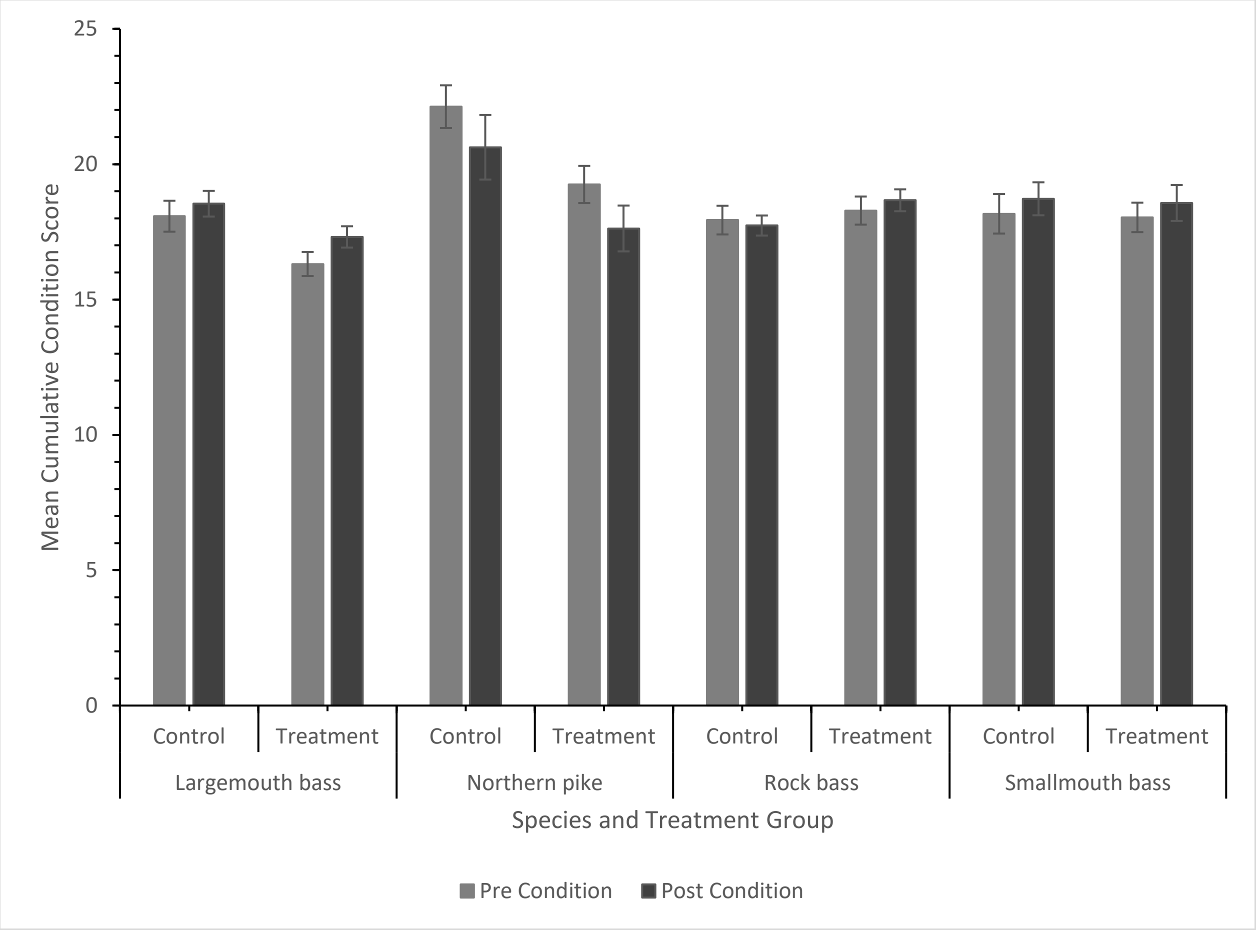

Figure 3-5: Mean pooled condition scores for each species flushed through (treatment) and over (control) the VLH turbines at Wasdell Falls on the Severn River in Ontario showing before and after scores plotted with standard error.

General Discussion

The VLH series of turbines continue to show promise in its purported fish friendliness. In my assessment of the risk posed by the VLH turbines, I found risk to the species studied at this location to be quite low. Entrainment events did not occur in any of our tagged fish and fish usage of the VLH forebay was limited. As a result, the potential for entrainment was found to be quite low. Should a fish hypothetically become entrained, the second portion of this study found that it is likely that it would survive. Our direct mortality rate across all fish entrained (regardless of species) was very low (1.16%), and our delayed mortality rate was the same. This delayed mortality rate of the treatment group of 1.16% was lower than that of the control group (1.82%). Therefore, it seems likely that our handling had an effect on delayed mortality. Nonetheless rates were the same across treatment and control groups therefore entrainment through the VLH turbine did not cause an increase in delayed mortality here. It is important to remember that we conducted the experimental entrainment with the worst operating parameters regarding entrainment location and blade opening conditions identified during the entrainment studies in France. (Lagarrigue, 2013; Lagarrigue & Frey, 2010; Lagarrigue et al., 2008). Therefore, under many operating conditions it is likely that the rates of mortality from entrainment would be even less. In comparison to the tests in France, our rates of mortality are very similar. It seems that the most gibbous fish did fare better as they had no instances of spinal deflections and few bruising and blade strike related injuries. On the other hand, the more elongate fish experienced some spinal deflections and the only direct mortality that we saw was that of a northern pike. Therefore, it seems that adults of more elongate fish are the most vulnerable to mortality caused by entrainment.

There were a number of important differences between the entrainment portion of this study and those carried out in Europe. In the tests in France the number of fish entrained was greater and hatchery fish with a good baseline condition were used for part of the study

(Lagarrigue, 2013). As a result, the differences between the rates that were found here and those in France, is likely a function of sample size. Ideally, I would have been able to entrain more fish but unfortunately fish capture was unpredictable, and fish were not generally caught in large numbers. The use of hatchery fish during testing in France allowed for a baseline good condition before entrainment with less handling and holding. This would likely have a reduced effect on delayed mortality than the amount of handling that was carried out in this study. However, since many of the species studied here are not common in hatcheries, and due to cost, this was not a viable option. The studies in France did look at different injury types observed but did not carry out quantification of the specific injuries. In future studies of entrainment effects, it would be beneficial to hold fish in pens which are less likely to cause injuries.

There were other limitations in this study, namely that habitat usage and movements that I found for forebay usage are very site specific. However, future studies should look at forebay usage of this type of turbine at other sites, as the forebay usage of low head turbines in general is a corner of the literature which is greatly lacking.

Future studies should explore interactions of different species with this turbine to assess risk to other fish assemblages and in particular the entrainment of juvenile species should be examined. The low maximum sustained swim speeds of juvenile fishes coupled with a propensity for outmigration in some species make this age class more likely to become entrained through VLH turbines. Being proactive in determining risk of new hydroelectric technologies to Canadian fishes is a responsible way to mitigate risk to our natural resources. The performance of the Very Low Head turbine in relation to fish passage bodes well for future developments in low head hydropower. The combination of benefits surrounding the VLH turbines including low construction cost, ability to make use of underutilized sites, and lower environmental footprint, make it a suitable candidate for a wide range of low head locations across Canada. For example, there is increased interest in retaining instream barriers around the Great Lakes region to halt the spread and reproduction of invasive species. This type of turbine could possibly add some dual functionality to these barriers. However, managers should also consider the habitat connectivity issues that arise with the creation of new barriers at low head sites which would have a greater impact upon the fish community. Conversely at sites where there are pre-existing structures which are unlikely to be removed, the implementation of a VLH turbine could be an option depending on the traits of the species present at the site. Using the data gained here, managers should be able to make more informed decisions to assess risk to fish from this type of turbine.

In terms of expanded future use in Canada the VLH turbine could cause socioecological changes in remote areas of Canada where access to reliable hydroelectric generation with a low ecological footprint is difficult. Here the VLH turbines could provide remote communities with an alternative to the widespread diesel generators (Mariano & Cañizares, 2013). In combination with other renewable power sources and storage systems, communities may have the ability to more self sufficient rather than relying upon constant imported fossil fuels. It is in these remote communities that the beneficial socioecological effects of the VLH turbines could be most substantial. These cleaner energy sources have a large role to play in fight against climate change and working towards sustainability in power generation.

Conclusion

The literature on entrainment risk caused by the VLH series of turbines is growing. With the larger evidence base supporting fish friendliness, this technology has great potential. For this fish community, the risk of entrainment was quite low and the mortalities and injuries resulting from entrainment were minimal. The species covered in this study are present across a wide range area of North American and as a result many low head sites in this area could likely support this type of turbine with minimal detrimental effects to related fish communities.

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